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Final Report on the Development of a 250-kW Modular, Factory-Assembled Battery Energy Storage System

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Final Report on the Development of a 250-kW Modular, Factory-Assembled Battery Energy Storage System

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Abstract

A power management energy storage system was developed for stationary applications such as peak shaving, voltage regulation, and spinning reserve. Project activities included design, manufacture, factory testing, and field installation. The major features that characterize the development are the modularity of the product, its transportability, the power conversion method that aggregates power on the AC side of the converter, and the use of commonly employed technology for system components.

Acknowledgments

Sandia National Laboratories would like to acknowledge and thank Dr. Russell Eaton and Dr. Christine E. Platt of the U.S. Department of Energy's Office of Utility Technologies for the support and funding of this work. We would also like to acknowledge Pacific Gas & Electric for its active role in the design and development process of this initiative by cost-sharing long-term characterization and testing at its Modular Generation Testing Facility in San Ramon, California. Thanks are also due for the Electric Power Research Institute's sponsorship of the data acquisition system used for two of the eight modules within the AC Battery container.

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Acronyms

BES	battery energy storage
BESS	battery energy storage system
cfm	cubic feet per minute
DOD	depth of discharge
DOE	U.S. Department of Energy
EPRI	Electric Power Research Institute
FPGA	field-programmable gate array
fpm	feet per minute
GTO	gate turn-off thyristor
GUI	graphical user interface
HVAC	heating, venting, and cooling
IEEE	Institute of Electrical and Electronics Engineers
IGBT	insulated gate bipolar transistor
LAN	local area network
MGTF	Modular Generation Test Facility
PC	personal computer
PCD	pulsed charge/discharge
PCS	power conversion system
PG&E	Pacific Gas & Electric Company
RAM	random-access memory
R&D	research and development
RMS	root mean square
RTU	remote terminal unit
SCADA	System Control and Data Acquisition
SCR	silicon-controlled rectifier
SOC	state of charge
SOW	statement of work
SNL	Sandia National Laboratories
SQL	structured query language
T&D	transmission and distribution
THD	total harmonic distortion
UV	ultra-violet
VAR	volt-amp reactive
VGA	video graphics array

Preface

Omnion Power Engineering Corporation, through the sponsorship of the U.S. Department of Energy and Sandia National Laboratories, designed and developed the AC Battery concept (a factory-assembled, modular, outdoor, pad-mounted battery energy storage system). Pacific Gas & Electric also played an active role in the design and development process by cost-sharing characterization and long-term testing at its Modular Generation Test Facility in San Ramon, California. Data monitoring for the system was further enhanced through Electric Power Research Institute sponsorship of an intensive data acquisition system for two of the eight modules within the AC Battery container. Omnion, Sandia National Laboratories, Pacific Gas & Electric, and Electric Power Research Institute all collaborated on the development and implementation of the test plan. A final report on the field test was prepared by Pacific Gas & Electric.

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Final Report on the Development of a 250-kW Modular, Factory-Assembled Battery Energy Storage System

1. Introduction

In early 1991, Omnion Power Engineering Corporation began developing the concept for what was to become a 250-kW modular, factory-assembled battery energy storage system (BESS) known as the PM250. While development of the PM250 concept was Omnion's responsibility, a second company, AC Battery Corporation, was organized for the express purpose of providing turnkey BESSs for the 1990s and beyond. Omnion's development of the AC Battery concept was initiated in early 1991 with support from the U.S. Department of Energy (DOE), Sandia National Laboratories (SNL), and Pacific Gas and Electric (PG&E). The Electric Power Research Institute (EPRI) contributed to a data acquisition system during the field test of the prototype.

The final product delivered under this contract was an AC Battery Transportable BESS—trademarked the AC Battery Corporation's PM250 Power Management System. The PM250 is a fully integrated, pre-packaged, factory-assembled BESS capable of being shipped to the customer's site and installed with a minimum of field labor (see Figure 1-1). Once on-line, it is capable of performing multiple functions including peak shaving, voltage and frequency regulation, and spinning reserve for a utility or customer system.

The initial AC Battery system concept, as described in depth in Appendix A, uses high-volume production components of proven reliability. These components are factory assembled under rigorous quality control standards to create a fully operational, modular BESS. A single AC Battery PM250 container, when shipped to the site, installed, and connected to a centralized system controller, constitutes a 250-kW/167-kWh BESS.

Unlike traditional battery storage systems that bus together numerous battery strings through specialized high-voltage DC switchgear and custom-built converters, the AC Battery system aggregates AC power from multiple AC Battery modules housed in a container. Multiple containers are then paralleled to achieve the desired system capacity. Multiple container installations use a 250-kW basic building block that can be configured to build capacity up to 10 MW. The container is fully assembled and factory tested to minimize field startup time. The original concept was driven by the premise that factory assembly and pretesting prior to shipment could—at substantially lower cost—improve overall product quality and reliability, two product attributes widely viewed as nemeses for existing battery system designs.

Using Delco 2000 maintenance-free, flooded lead-acid battery technology entirely eliminated the need for watering and electrolyte agitation. Battery replacement is easily facilitated through a newly developed "rack 'n' stack" battery assembly design. New batteries may be installed by either substituting an entire AC Battery module or replacing individual battery trays at a local service center near the customer's installation site. Spent batteries are returned by AC Battery's service personnel to a Delco manufacturing facility for recycling into new product.

1.1 Project Overview

This BESS concept was originally conceived of as a 500-kW/500-kWh containerized battery system composed of 36 14-kW/kWh modules, each containing 21 12-V Group 31 batteries and a power conversion system (PCS) (see Figure 1-2). The concept called for restricting overall container weight to the maximum legal limit allowable for over-the-road shipment without special permitting for size

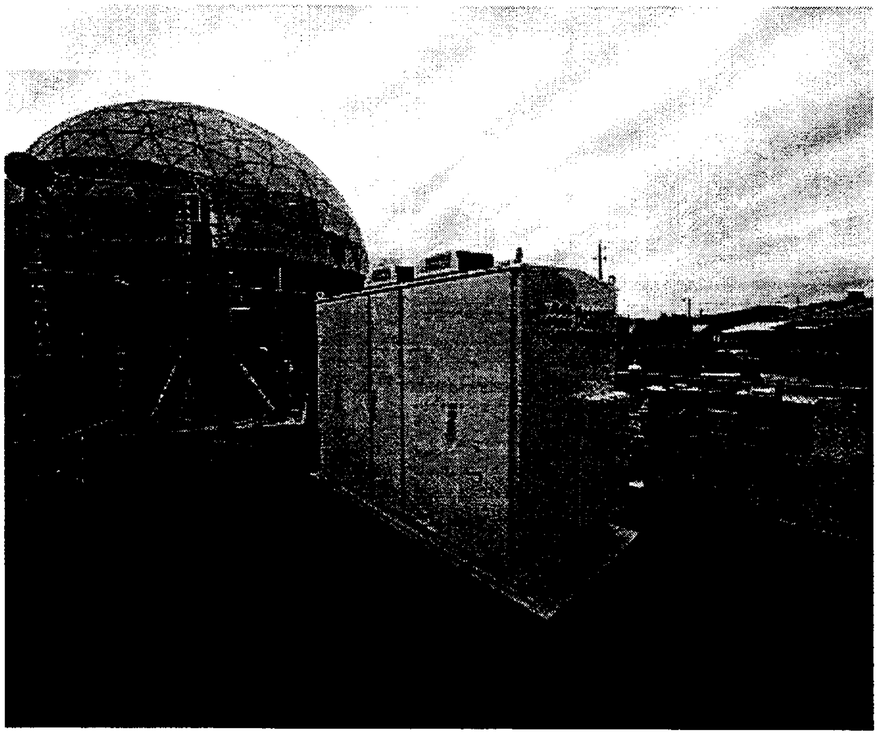

Figure 1-1. AC Battery System Installation.

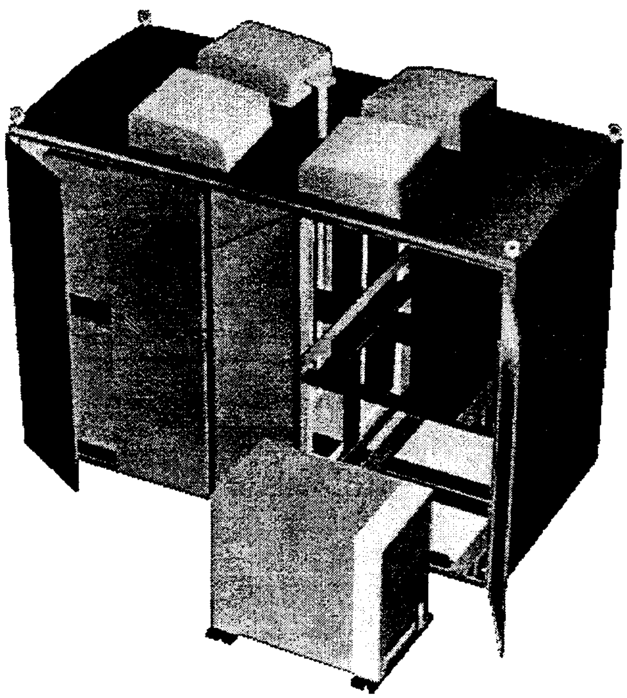

Figure 1-2. Rendering of Original Containerized Concept.

or weight. What evolved was a product easily transported by truck and suitable for commercialization but with the reduced capacity of 250 kW/167 kWh. The final product consisted of a containerized design with eight modules, each holding 48 12-V flooded lead-acid batteries and a modular PCS. The initial concept was refined in accordance with criteria that called for modification of the specifications only when goals were unachievable or a preferred design or engineering solution was identified. This final report will explain those factors that contributed to the reduction in original system-specified capacity and will offer justification of the advantages of stabilizing the design around its present configuration.

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2. Design and Development

2.1 Container Development

After development of the initial AC Battery system concept, the integrated system design evolved substantially. As development proceeded from the initial concept toward realization in hardware, the product took a refined form, incorporating new techniques for power conversion, heat transfer, and packaging. The following summaries highlight the evolution of the AC Battery from its initial conceptual design to its final form as delivered under this contract.

The original design concept called for a container design that would be relatively compact and lightweight. It was intended to serve as an envelope and support for the modules, with a size and shape suitable for easy transportation, yet possessing sufficient strength and rigidity. Additionally, it was to provide tamper-proof protection for batteries and electrical gear while allowing easy access to all internal components. Other features included a 20-year design life, low maintenance requirements, and insulation to minimize the required heating and cooling of the batteries. It also had to provide ventilation for exhausting waste heat from the PCS and any gases given off by the batteries.

2.1.1 Transportation and Handling Considerations

The original project goal was to design and fabricate a modular, containerized BESS rated at 500 kW/500 kWh that could be easily transported via truck to an installation site and quickly installed and commissioned. The concept called for a system that would be completely factory-assembled and pretested prior to shipment—a containerized system that could be easily transported via truck and quickly unloaded and set up. The initial thoughts were that the container would house 36 battery modular assemblies—each with an integral PCS rated at 14 kW. The container would be designed for outdoor operation in wide-ranging temperature conditions while maintaining operating temperatures inside to allow the operation of the modules within prescribed narrow operating limits suitable for maximized battery performance.

After reviewing battery test data on capacity versus depth of discharge (DOD) and cycle life, it was concluded that the flooded lead-acid battery design was not capable of a 1:1 ratio of kW to kWh. It became apparent that resizing and rerating the container was necessary since the ratio is, at best, 1:0.67 kW to kWh—even with a revised battery plate design.

Calculations for module sizing based upon the power rating of the individual batteries showed that 864 batteries would be required to obtain a 500-kWh system rating if operated at 250 kWh for 2 hr and 1,152 batteries to achieve a 500-kWh rating for 1 hr. This is the equivalent of 18 or 24 48-battery modules, respectively. As the development proceeded, it became apparent that some changes and improvements would be in order due to weight and handling/shipping considerations. Two problems existed with the 1,152-battery option.

(1) The first problem was the volume of the container. In order to fit 1,152 batteries into a container, it was necessary to design the container to fit on a double-drop, low-boy trailer. This meant that the shape of the container would need to jog up at both ends of the container. Figure 2-1 shows the shape of the container required to get all the batteries into the container.

(2) The second problem was one of weight. With 864 batteries, it is possible to move the container and modules in two trucks. With 1,152 batteries, a low-boy trailer and two additional trucks were required to move a container.

2.2 System Container

Figure 2-2 shows the revised container design. Dimensions are 10 ft, 10 in. high; 14.5 ft long; and 7 ft wide. Based on this information and trade-offs for transportation and handling, the container design was modified and the system derated to 250 kW/ 167 kWh.

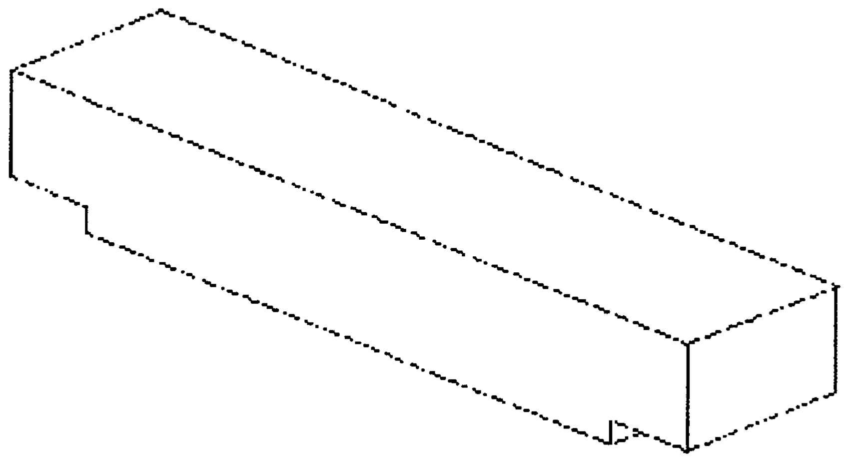

Figure 2-1. Anticipated Enclosure Configuration for 500-kW Container.

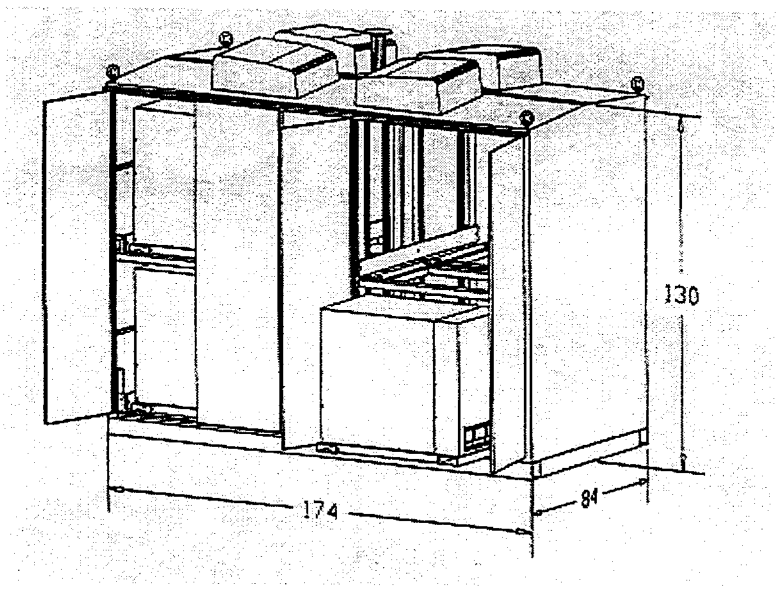

Figure 2-2. Revised Container Design (measurements shown are in inches).

These changes to the container yielded the following advantages:

(1) Easier transportability to the site and on site. Only one truck would be required for transporting the system to the job site.

(2) All modules come preinstalled in the container, enhancing shipping security, product integrity, and reliability, and also minimizing handling and installation site work.

(3) The cooling system can use a shorter, simpler ducting system. This simplifies the task of ensuring temperature uniformity among batteries and modules.

Another added feature was the ability to load and unload modules from one side of the container rather than both sides. This minimizes the needed site improvements and allows the fitting of more containers in a given area, greatly increasing the overall power and energy density.

Containers can be placed end-to-end with minimal space between them. Access to all components of the container can be accomplished from the sides or top of the container. Figure 2-3 is a skeletal view of a container frame.

Connections to the container consist of a 250-kVA, 480-VAC three-phase service drop and connections to a system control and data acquisition (SCADA) system. Where multiple containers exist at a site, the SCADA system is connected to the first container only. The additional containers are then controlled by the first container. This makes the first container a master and the additional containers slaves. All containers have the capability of being masters or slaves as desired.

Design of the system configuration, system topology, and power conversion is covered under U.S. Patent No. 4,894,764, dated January 16, 1990, and precedes work under this contract.

2.3 Modules

The final module design contains 48 batteries stacked in 4 layers of 12 batteries. This represents a change from earlier concepts that called for a single layer of 21 batteries and makes it a stronger module. To circumvent potential complications in production and serviceability, a novel structural design incorporates layers of battery trays, which can be preassembled, wired, and stacked to form a rigid unit. The module is configured so that it can be handled easily by a forklift and shipped on a flatbed truck.

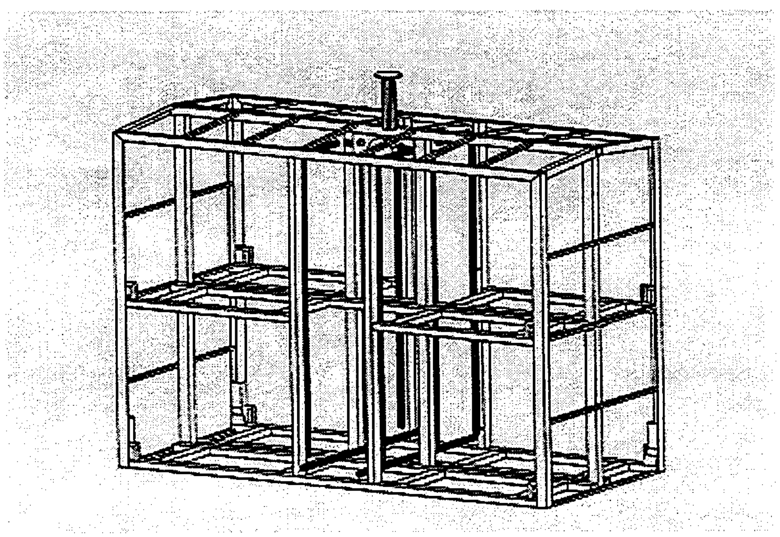

Figure 2-3. Skeletal View of Container Frame.

Figure 2-4 shows the module configuration. Each module is 58 in. wide, 51 in. high, and 40 in. deep and carries a rating of 32 kW/21 kWh at the 1-hour rate. On one end of the module is the PCS for charging and discharging the batteries (see Figure 2-5). A centrifugal blower in each module draws conditioned air from the container heating, venting, and cooling (HVAC) system and blows it across the batteries before returning to the HVAC system.

By incorporating 48 batteries per module (vs. 21 batteries in earlier design concepts), the capacity was increased. Only eight modules are used, resulting in both material and labor cost savings.

Reconfiguration and redesign of the modules produced the following benefits:

(1) Higher DC voltage, higher energy density, and reduced PCS cost.

(2) A dual-circuit HVAC system tailored to the differing needs of the PCS power train and the batteries.

2.4 Battery Validation Testing

The battery selected for the AC Battery system was the Delco 2000, manufactured by the Delphi Energy and Engine Management Systems division of General Motors. The Delco 2000 was chosen because its reliability and cycle performance closely match the characteristics required for voltage regulation, peak shaving, and spinning reserve applications.

The Delco 2000 is a high-production-volume, maintenance-free flooded lead-acid battery. It does not require watering or electrolyte agitation that are characteristically needed by stationary battery systems. It is capable of multiple, successive discharges over a short period of time without requiring a complementary recharge.

Statistics on battery cycle life and long-term performance for repeated cycling as they relate to the AC Battery application were not as detailed as was expected going into the project. Factors affecting battery discharge and cycle-life performance include:

(1) Environmental Conditions (e.g., temperature)

(2) Shelf Life/Self-Discharge

(3) Depth of Discharge

(4) Number of Discharge Cycles

(5) Rate of Discharge

(6) Recharge Methodology

The anticipated operating parameters and system performance expectations were considered simultaneously with the known capabilities of the selected battery. To validate battery performance and more closely define system design requirements, tests were designed to accomplish the following:

(1) Study the thermal load characteristics of the batteries to determine container heating and cooling requirements.

(2) Determine internal enclosure airflow patterns to optimize battery cooling and equalize the temperature gradient throughout the container.

(3) Establish DOD versus cycle life warranty information.

(4) Establish the potential for hydrogen gassing and identify operating conditions and electrical conditions that tend to promote gassing.

(5) Identify failed or nonperforming batteries.

(6) Develop and test the battery monitoring system.

(7) Define the impact on battery cycle life of use for frequency regulation.

(8) Develop an advanced charging algorithm.

2.4.1 Battery Thermal Testing

A full Battery Thermal Test Report can be found in Appendix B of this report. Conclusions drawn from the report include:

(1) The total battery contribution to heating within the container is approximately 24,000 Btu/hr (891 W × 8 modules × 3,600/1.055) for a period of 5 to 6 hours for a daily average of 1,013 Btu/hr for those days that the batteries are recharged. Taking into account the narrow range of ambient-to-discharge air temperature, a nominal cooling capacity of about 12,000 Btu/hr was determined to be adequate to maintain the ambient temperature within acceptable limits.

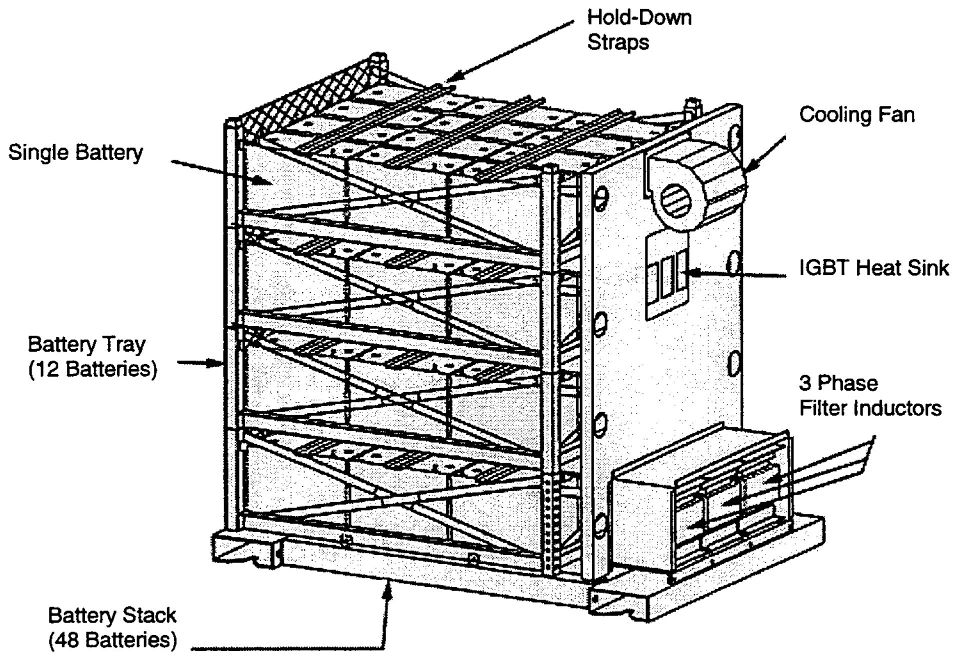

Figure 2-4. Module Showing Rack 'n' Stack Design.

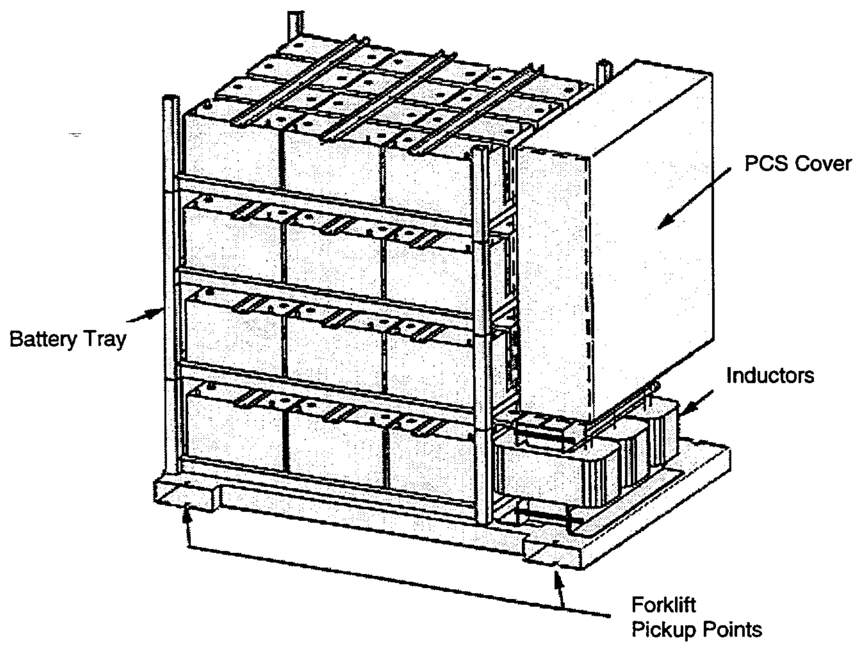

Figure 2-5. Module Showing PCS Mounted with Redesigned Battery Trays.

(2) Airflow of approximately 20 cubic feet per minute (cfm) over the batteries is required to stabilize battery temperature with repeated cycling to 80% DOD.

2.4.2 Battery Cycle-Life Testing

Cycle-life testing of batteries in modules was conducted at Delphi's Technology Development Center in Indianapolis, Indiana (see Figure 2-6). Testing of the Delco 2000 battery to simulate the AC Battery environmental and operational conditions involved hundreds of man-hours over a 2-yr period and dozens of tests. Analysis of the results led to several changes in the manufacturing and assembly of the Delco 2000 battery with corresponding improvements in product quality (a reduction in product returns due to infant mortalities, as measured by Delphi) and a substantial improvement in battery life. A synopsis of the recharging method adopted for use in the AC Battery system is provided below.

Constant-current charging was used effectively in 50% and 80% DOD cycle-life testing, with a significant increase occurring in cycle-life retention. Cycle life of lead-calcium low-maintenance batteries is significantly improved with charge regimes that feature higher voltages in constant-current and constant-voltage charge regimes. The problem with higher voltages was found to be caused not so much by plate damage as by water loss resulting from excess gassing. Pulsed charge/discharge (PCD) charging regimes offer the benefits of higher voltage and a chance to reduce gassing by reducing the charge time. Tests were conducted at the Delphi Technology Development Center to compare water loss in constant-voltage charging to that with PCD charging.

Observations and conclusions include the following:

(1) Charge time for constant-voltage charging was arbitrarily chosen based upon best success in the past. Typical recharge time for life cycling was 24 hr at 16 V and

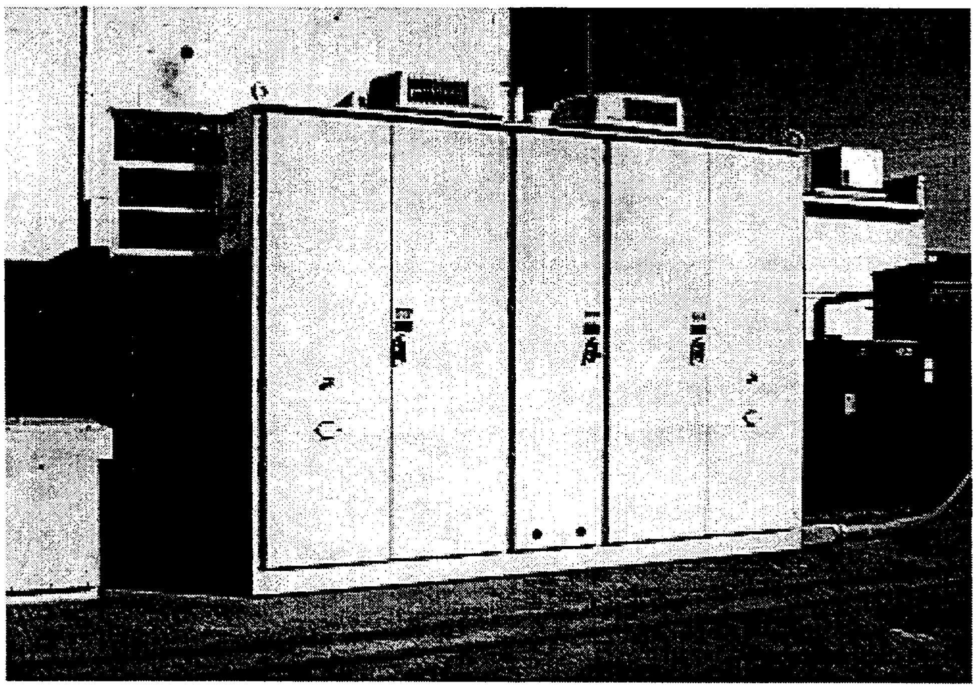

Figure 2-6. Module Test Chamber Outside Delphi's Technology Development Center.

25 A for 80 or 100% DOD. The charge time was reduced to 12 hr for 50% DOD cycling with constant-voltage charging. By the above rule of thumb, water loss would be even greater.

(2) Very little cycling has been done at 100% DOD with PCD charging due to emphasis being placed on 80% DOD and less. A more meaningful comparison at 100% DOD would have set the recharge for 110% PCD, which would reduce gassing. Several test runs at 100% DOD inserted at 25- and 50-cycle intervals (between normal cycles of 80% DOD) with 110% recharge successfully reduced gassing rates, but those data are not presented in this report. Figure 2-7 is a module test graph of DOD vs. discharge time.

(3) The PCD charging regime results in better capacity retention during cycling, but the constant-voltage regime does not. An experiment was conducted to optimize pulse times for charge and discharge and the charge/discharge current for destratification and capacity retention.

(4) Production Delco 2000 batteries will sustain 80% DOD for 50 cycles or less when charged at 16 V, 25 A. The same battery design will sustain 80% DOD for 180–200 cycles when charged with the PCD regime. This PCD regime accounts for a reduction in water loss by as much as 50% and reduces charging time by approximately 75%.

(5) Encapsulation of the positive/negative battery grids will be used in the design for AC Battery and other applications where high temperature is not a problem.

The testing of the Delco 2000 battery PCD regime on batteries was found to more than double the expected cycle life of batteries when control of discharge rate and ambient conditions is maintained. The success of the work conducted at the Delphi Technology Development Center led to issuance of a patent for the battery recharge method. The proprietary work conducted under this study is covered under U.S. Patent No. 5,499,234, dated March 12, 1996.

2.5 Power Conversion System

A decision was made to redesign the PCS control board to incorporate a programmable chip to permit changes to control logic to be made in software instead of hardware. Compared to previous designs, the new PCS hardware design is greatly simplified. By integrating much of the control and protection logic onto a field-programmable gate array (FPGA) chip, component count—and its corresponding cost—are reduced, while reliability should increase.

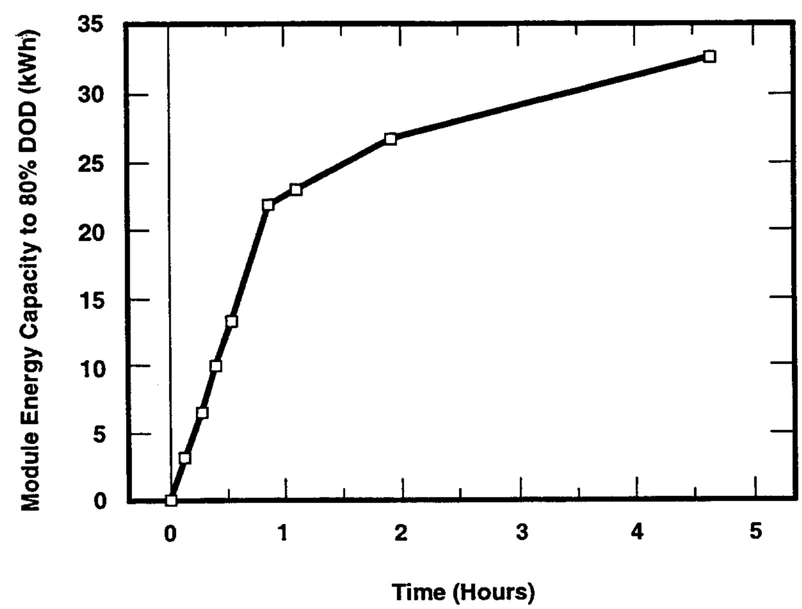

Figure 2-7. Module Test Graph of DOD vs. Discharge Time.

In addition, a new phase-locked loop-hysteresis current regulator has been developed using extensive computer modeling and simulation. Its implementation results in further parts count reduction and reduced circuit complexity.

Advanced insulated gate bipolar transistor (IGBT) power-conversion technology with microprocessor control developed under previous SNL contracts was used in the PCS design. The PCS design was optimized for utility applications such as frequency regulation, spinning reserve, and peak shaving. The PCS has full four-quadrant operation with automatic AC-bus volt-amp reactive (VAR) regulation.

Many higher-level control functions were also moved from the PCS control to the container-control computer. As a result, these computation-intensive yet less time-critical tasks can be performed in a centralized location, allowing greater PCS simplicity. Another advantage is that it simplifies the tailoring of the AC Battery system to a wide variety of applications. Fiber-optic communication links connect the modules to the module-control computer.

A graphical user interface (GUI) was added to allow multilevel control while clearly displaying parameters of interest. The display emulates eight module-control panels and a main-system panel. Status targets and digital readouts show, at a glance, the operating conditions for each of the modules. An X-Y display will show the four-quadrant output of the container and modules. The total system display shows overall performance while continuing to monitor the individual modules. Commands may be issued in kW, kVAR, kVA, power factor, phase angle, or DC amperes. The computer makes all the necessary conversions.

Design of the modules produced the following benefits:

(1) Skewing of the module outputs for lower distortion and higher power conversion efficiency. (See Appendix C for the Power Conversion Skewing Report.)

(2) A new transformer design that replaces the reactors in the PCS while delivering a 480-VAC output.

(3) Soft control of the PCS using FPGAs to replace numerous discrete-logic devices, permitting easy reprogramming of power conversion and module-control software.

(4) Centralized high-level control, providing greater system flexibility while minimizing the cost and complexity of the PCS.

2.6 Skewing of the Module Outputs

Skewing is a technique in which the phasing of each of the eight modules is staggered, or skewed, by 1/8 of the switching period. When all waveforms from the eight modules in the container are combined, the high-frequency components created from switching tend to cancel, while the 60-Hz line frequency component remains. By using skewing, lower-frequency switching is possible, resulting in lower switching losses and lower-cost reactors.

The skewing of bridge outputs was modeled to find out what effect various parameters would have on the output waveform both at the output of a single module and at the output of the container. The goal was to keep the total harmonic distortion (THD) of the current output under 5%.

Modeling has shown that:

(1) Reducing inverter frequency allows use of more conventional cores in the reactor and, as a consequence, permits use of a thicker and less expensive core material.

(2) Reducing inverter frequency also results in higher PCS efficiency because of the reduction in switching losses.

(3) Both inductance and frequency of operation can be reduced while keeping the current THD below 5%.

(4) By reducing the inductance, the cost of the reactor should be reduced proportionately.

(5) There is a cost trade-off between reactor size and IGBT rating. The minimum configuration of the magnetics in terms of inductance and frequency is 200 μH per phase of inductance and 3,000 Hz operating frequency. This will require a 200-A IGBT. If the inductance is increased to 400 μH and the frequency to 4000 Hz, a 150-A IGBT would suffice.

Modeling also provided data with which to design the reactor.

2.7 Transformer Design

Another area for potential weight, size, and cost savings is the magnetics. Past PCSs have used separate reactors for each phase. The outputs of each of the phases were then sent to a three-phase transformer to provide isolation and voltage matching.

Reexamination presents three options with regard to the reactor:

(1) Build three separate reactors, as has been done in the past.

(2) Combine the three separate reactors to make a three-phase reactor. This would reduce the parts count.

(3) The reactors could become leakage inductance in a transformer.

The transformer specified was an isolation transformer with a stepped-up 480-V output. (It was also specified to provide DC isolation.)

2.8 HVAC System Modifications

An important consideration in a confined BESS is dissipation of heat generated by the batteries during charge cycles. A test was conducted on a scaled-down battery array to determine room temperature ambient airflow requirements to prevent overheating of the batteries under the worst-case loading conditions. Worst case is expected to occur when using the AC Battery system for frequency stabilization because this subjects the battery to repetitive charging and discharging at a fairly high duty cycle. A brief description of the Battery Thermal Test follows. The full Battery Thermal Test Report can be found in Appendix B.

For this test, a battery (string of 47 batteries) was discharged from 100% state of charge (SOC) to 80% SOC and then recharged. The discharge/recharge cycle was repeated for 8 hr in a routine that returned the battery to approximately 80% SOC. Battery voltage was monitored to ensure that the battery was not being discharged or charged on a cumulative basis.

The effects of temperature on battery charge cycling were studied. The batteries were positioned in an airflow chamber where ambient air was blown past the batteries by a variable-speed fan with air velocity measured at the discharge. Temperature probes were installed at the inlet, outlet, and battery post, and in between the batteries to measure heat dissipation and battery temperature. Three levels of airflow were evaluated after 5 to 6 hr of cycling. Sample test data is shown in the following table:

Air Velocity (fpm)	100	200	400
Airflow (cfm)	4.86	9.72	19.44
Q (Btu/min)	0.87	2.28	3.17
Q (Watts/3 batteries)	15.0	40.0	55.7
Q (Watts/module)	240	640	891

Some of the test observations are as follows:

(1) The battery temperature did not stabilize with 4.86 cfm.

(2) Variations in airflow barely stabilized with 9.72 cfm and stabilized at about 4 hr at 19.44 cfm. Airflow then tracked the ambient temperature.

(3) In each case, the battery temperature as indicated by the probe located between batteries reached about 42°C and recovered to about 38°C while on the overnight charge with no ventilation.

(4) The charge/discharge cycle used here was 5-6 hr of operation with slow recharge, which is considered to be more severe than anticipated in commercial use.

The test yielded the following conclusions:

(1) The total battery contribution to heating within the container is approximately 24,000 Btu/hr for a period of 5-6 hr for a daily average of 1,013 Btu/hr. Considering the narrow range of ambient-to-discharge air temperature observed, it appears that a cooling capacity of about 12,000 Btu/hr should be adequate to maintain the ambient temperature within acceptable limits.

(2) The results helped to confirm the differing cooling requirements for the batteries and the PCS. Batteries have a much greater thermal mass, yet have a stricter requirement for optimal temperature range. By developing separate cooling systems for each, fewer compromises are required, and overall cooling efficiency can be increased.

(3) A further result of thermal testing was a reduction in the system ambient operating specifications from -20–120°F to 18–110°F. Sprayed-foam insulation on the interior of the container skin was determined to be a cost-effective solution for holding internal container temperatures within the reduced ambient operating range limits.

(4) The HVAC system was redesigned to eliminate use of outside air, thus eliminating vents and maintenance associated with filters. The power bridges need little conditioning and therefore add little load to the requirements for the batteries and PCS. Air inside the container will be heated and cooled as necessary to maintain the 60–100°F optimal temperature range.

3. Final System Design

3.1 Container

The AC Battery container is a 250-kW, unitized BESS. This assembly provides the hardware and electrical apparatus necessary to source and sink AC kilowatts and VARs under user control. The system is composed of eight AC Battery modules, a hydrogen venting and detection system, and a heating and cooling system all enclosed in a single outdoor container as shown in Figure 3-1 and Figure 3-2. A mechanical drawing of the container can be found in Appendix D of this report. Structural safety analysis calculations for the container can be found in Appendix E. The power cable termination panel and power transformer for system controls and components are shown in Figures 3-3 and 3-4.

Each AC Battery module contains 48 batteries and a PCS. The system is called an AC Battery system because the input to and output from the modules is AC power. Capacity within the container is increased by bussing AC modules together rather than the more conventional approach of bussing additional battery strings together.

The primary advantage the AC Battery system has over a conventional BESS is that the AC Battery system is factory-assembled. Factory conditions offer a more controlled environment leading to lower manufacturing costs and higher proven reliability. The AC Battery system size was chosen so a single AC Battery container would fit on a truck with all the modules loaded in the container. This results in minimum field labor when installing a BESS. A container is designed to be removed from the truck, set up, and ready for power connections by a team of two trained people in 4 hours.

3.1.1 Electrical Characteristics

(1) Input/Output Voltage:

480 VAC, 3-Phase ± 10%.

(2) Frequency: 60 Hz ± 2 Hz.

(3) The PCS-generated harmonics measured at the system's AC interface, when operating at nominal rating power, do not exceed a total harmonic current distortion of 5%, a single-frequency current distortion of 3%, a total harmonic voltage distortion of 3%, or a single-frequency voltage distortion of 1%.

(4) Maximum Power: 250 kW.

(5) Energy Capacity: 167 kWh at the 1-hr rate to 80% DOD using 384 batteries in eight modules.

(6) Power Factor: Unity/controllable is used in both charge and discharge modes. Power factor can be operator-controlled from 0.0 leading to 0.0 lagging.

A one-line electrical diagram is provided in Appendix F of this report.

3.1.2 Physical Characteristics

(1) Size: 131"H × 174"W × 84"D.

(2) Weight: 41,000 lbs gross (est.).

(3) Shock and vibration resistant to 5 g's.

(4) The minimum required foundation load-bearing capacity is 600 lbs/ft^2 (est.).

3.1.3 Construction

(1) Welded structural/sheet steel and composite construction. Access for battery installation and service via hinged doors. Access for HVAC, power connections, data acquisition hardware, and system control via hinged doors or removable panels.

(2) Subframe suitable for transportation by truck.

(3) Vandal-resistant exterior surfaces.

(4) Finish: White enamel interior, Omnion beige ultra-violet (UV)-resistant acrylic enamel over primer.

(5) Insulated to R-4.

3.1.4 Environment

(1) Ambient conditions: 18–110°F with 0–100% humidity, rain, snow, hail, etc.

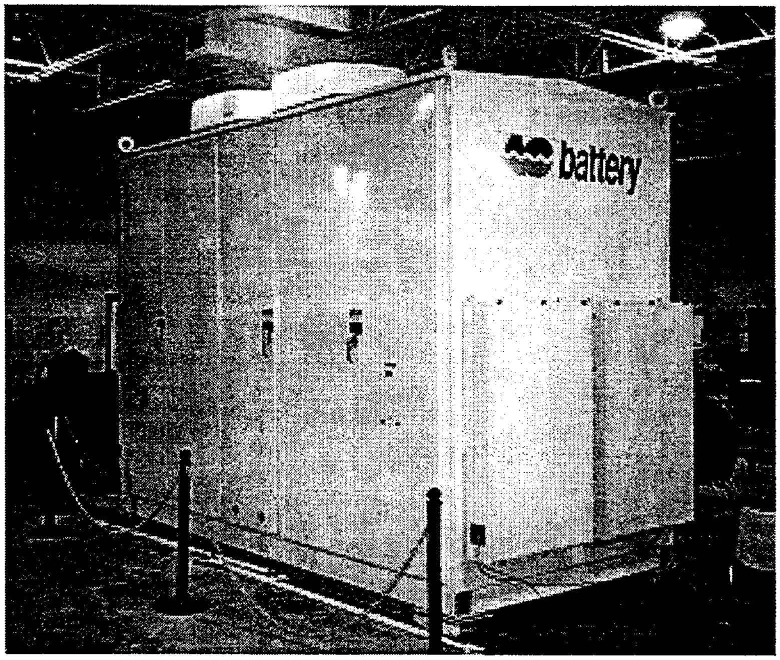

Figure 3-1. Final Container Design.

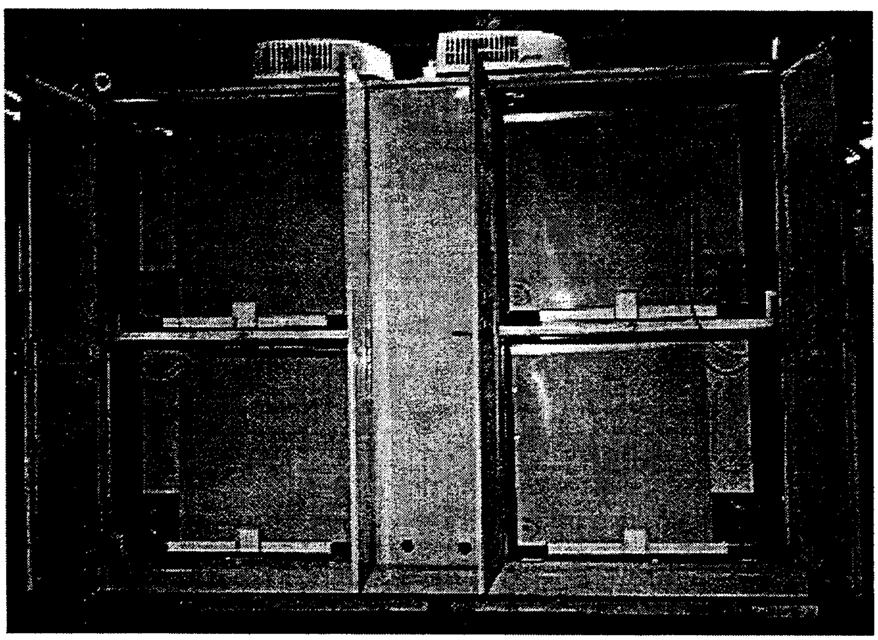

Figure 3-2. Container with Doors Open and Modules Loaded.

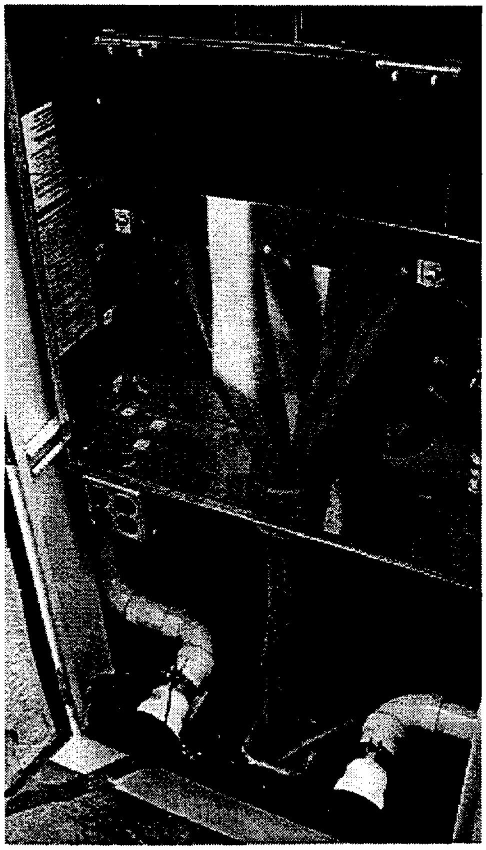

Figure 3-3. Power Cable Termination Panel.

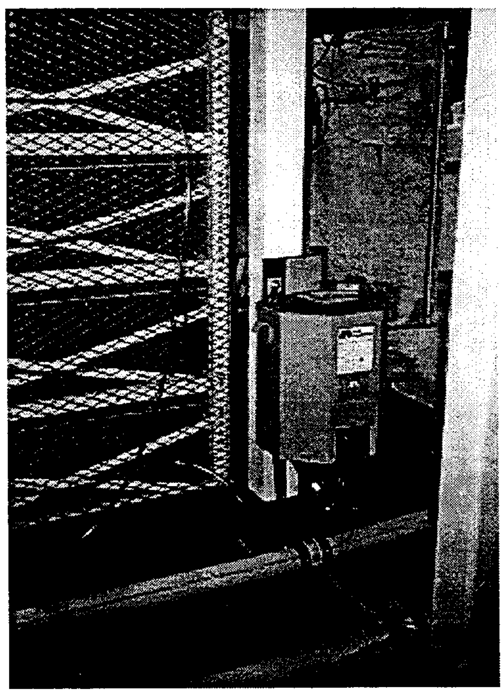

Figure 3-4. Power Transformer for System Controls and Components.

3.1.5 Thermal Considerations — HVAC

(1) Provision is made to maintain the interior of the container at 80°F ± 20°F. The maximum cooling capability is 18,000 Btu (est.) with the air-conditioning system consuming 2,600 W (est.) when operating at maximum output. Heating is provided by a 4,900-W (est.) heater.

3.1.6 Safety

(1) An eyewash and shower station is provided with the container. The eyewash and shower is a self-contained system.

(2) A first-aid kit is provided with each container.

(3) A basic powder for neutralizing acid spills is provided.

(4) A fire extinguisher is provided.

(5) Battery vents are plumbed to the outside of the container (see Figure 3-5). A hydrogen sensor is provided to put the container in the safest nonoperating state possible in the event that 1,000 ppm (est.) of hydrogen gas is detected inside the container.

(6) A smoke detector is provided to put the container in the safest nonoperating state possible in the event that smoke is detected inside the container (see Figure 3-6).

3.1.7 Handling

(1) Designed for handling with an overhead crane, straight lift on eyes or up to 30° off vertical. If a spreader is not used, a minimum of 18 ft must exist between the lifting eyes and the crane hook (see Figure 3-7).

3.1.8 Transport

(1) The container, fully loaded with modules, will ship on a standard double-drop semitrailer without requiring special transportation permits (see Figure 3-8).

3.2 Modules

3.2.1 General Description

Each module (Figure 3-9) is composed of a PCS and 48 batteries arranged in four layered trays of 12 batteries. All 48 batteries are connected in series to form one battery string.

(1) Size: 51"H × 58"W × 40" D.

(2) Weight: 3600 lbs (est.).

(3) Ambient Operating Conditions:

32-120°F, 0-95% relative humidity.

(4) Construction: Welded steel frame.

(5) Finish: Highly resistant to sulfuric acid.

(6) Provision was made in the module design for easy handling with a forklift.

3.2.2 Battery Characteristics

(1) Battery Type: Delco 2000 maintenance-free, flooded lead-acid.

(2) Battery Size: 13"L × 6.8"W × 9.5"H (Group 31).

(3) Battery Weight: 60.2 lbs.

(4) Minimum Battery String Voltage: 504 VDC (10.5 V per battery)

(5) Maximum Battery String Voltage: 816 VDC (17.0 V per battery)

(6) Required Cooling/Heating Air: Sufficient to keep the air flowing across the batteries between 60°F and 100°F.

(7) Charging Profile—When the module goes into Charge mode, the following steps occur: The battery is charged at the 25-A rate up to 16 V/battery. At 25 A, the power into the module starts at 13.25 kW, rising to 20.25 kW as battery voltage increases. If the battery starts at 80% DOD, this portion of the cycle takes approximately 2.3 hr. When 16 V per battery is reached, the voltage is held constant and the current drops until 3 A is reached. Power flowing into the module drops from 20.25 kW to 2.5 kW during this period, which lasts for 2 hr. At 2 A

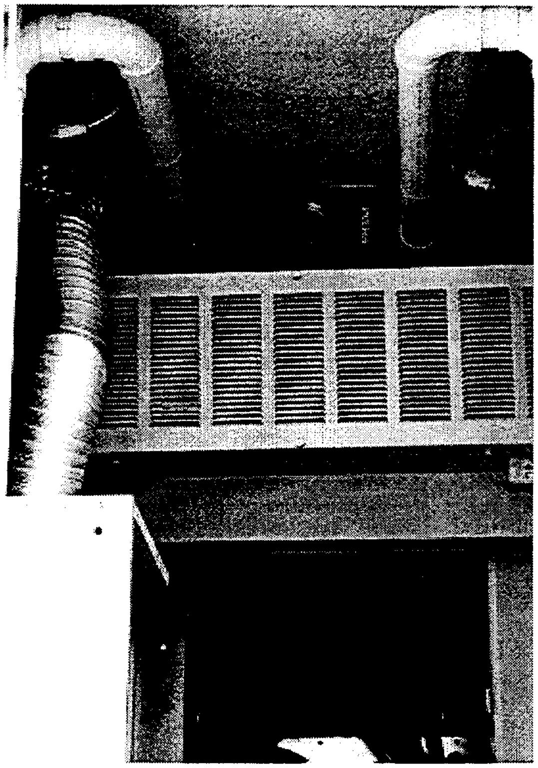

Figure 3-5. Air Curtain and Hydrogen Exhaust Blower and Piping.

Figure 3-6. Smoke Detector Mounted on Container Structural Support.

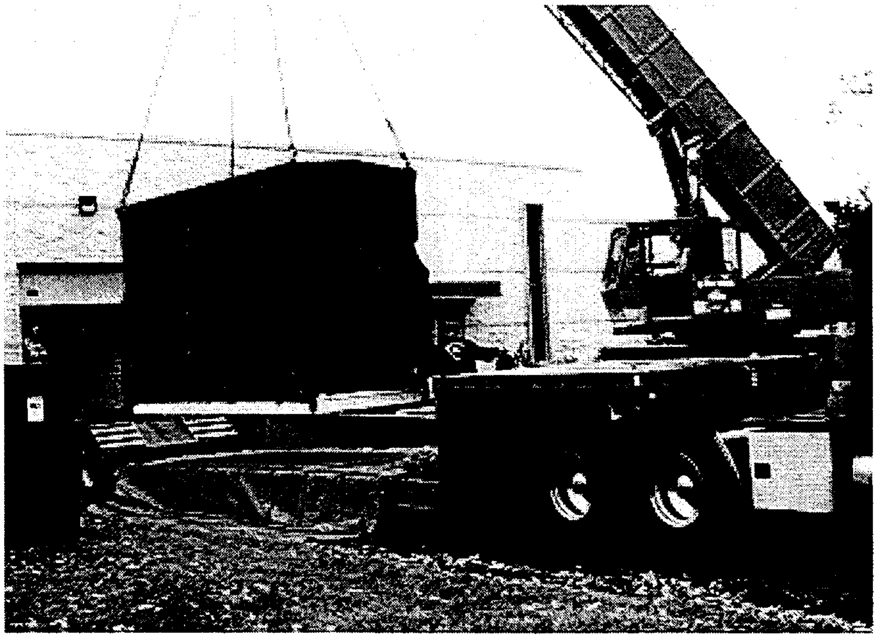

Figure 3-7. Lifting of AC Battery Container by Crane.

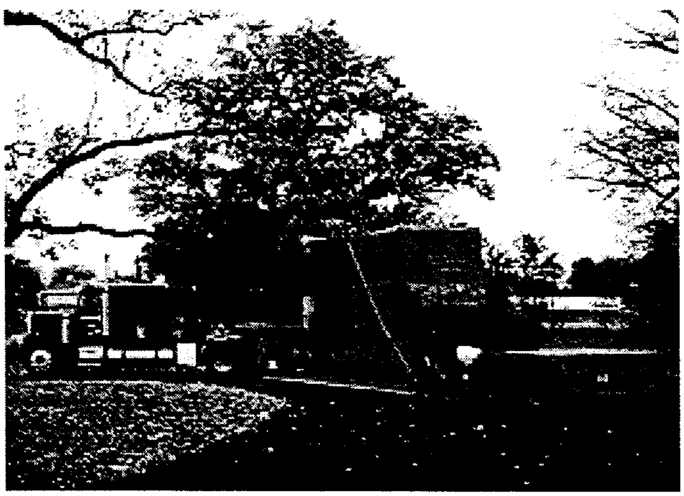

Figure 3-8. AC Battery System Loaded on Lowboy Truck.

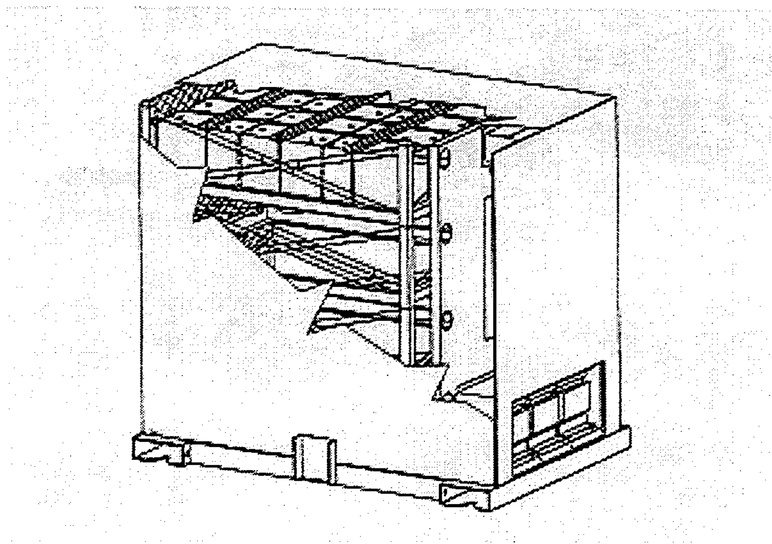

Figure 3-9. Module with Shields (Cutaway View).

and 16 V, constant-current charging begins and continues for approximately 1 hr. Power remains at 2.5 kW for this period.

3.2.3 Module Safety

Each battery string has fuses in the positive and negative DC leads at the converter. Located in the battery string are at least three fuses between battery levels. Module construction is such that while air can flow past the batteries, live electrical parts cannot be accessed from outside the module. Each battery has its vent connected via plastic tubing to the outside of the container. The DC circuit is not grounded.

3.3 Power Conversion System

3.3.1 PCS Characteristics

(1) Input/Output Voltage: 480/255 VAC p-p, 3-Phase 4-wire.

(2) Input/Output Frequency: 60 Hz.

(3) In addition to the 4-wire power connection, one fiber-optic duplex connection is made to each module.

3.3.2 PCS Configuration

(1) A single power conversion bridge capable of delivering a nominal 31 kVA is supplied per module. The PCS output parameters are:

- Operating Voltage: 255 VAC p-p ± 10%
- Number of Phases: 3

(2) Frequency: 60 Hz ± 2 Hz

- Nominal Operating Current: 37.6 AAC
- Maximum Operating Current: 41.3 AAC
- Power Factor: Full four-quadrant control
- Current THD: < 5%

(3) The PCS (Figure 3-10) is self-commutated and uses IGBTs in a full-bridge, transformerless circuit topology (with neutral connected). The PCS is an integral part of the AC Battery module. The output of the module is capable of being paralleled with other modules in such a way that high-frequency ripple in the output current waveform of any one module can be canceled by other modules in the container.

3.3.3 Operating Characteristics

Each PCS is capable of being controlled via a serial fiber-optic cable. The PCS includes the following modes of operation:

(1) Mode 1: Disconnect - No power at the AC terminals. The PCS has no method available to change out of this mode (control occurs at container level).

(2) Mode 2: Shutdown - AC contactor open. Control-system power remains energized. This condition is the result of a PCS fault or may be commanded over the serial cable.

(3) Mode 3: Standby - AC contactor closed. Control-system power energized. IGBTs are not switching. System can start converting power as soon as it is commanded to convert power.

(4) Mode 4: Run - AC contactor closed and current flowing.

3.3.4 Functions

The PCS is, as a minimum, able to accomplish the following functions:

(1) Shutdown - The PCS opens its AC output contactor under the following conditions and remains in the Shutdown mode until a reset is initiated:

- PCS Overtemperature Indication
- Synchronization Error
- Blown Fuse
- Power Supply Fault
- DC Ground Fault
- Overcurrent
- Lost Control Connection
- Serial Command
- Control Logic Trouble
- Shutdown Contact Closure (a dry contact closure disables the PCS as a hardware backup to the serial link)

(2) Standby - The PCS has its AC contactor closed with the IGBTs not switching. This mode is reached by serial-port command.

(3) Run - In this mode the PCS operates normally. This mode is reached by serial-port command. In this mode the converter is given a kVA level and a power factor for operation. In addition, each phase can be independently controlled in magnitude if desired.

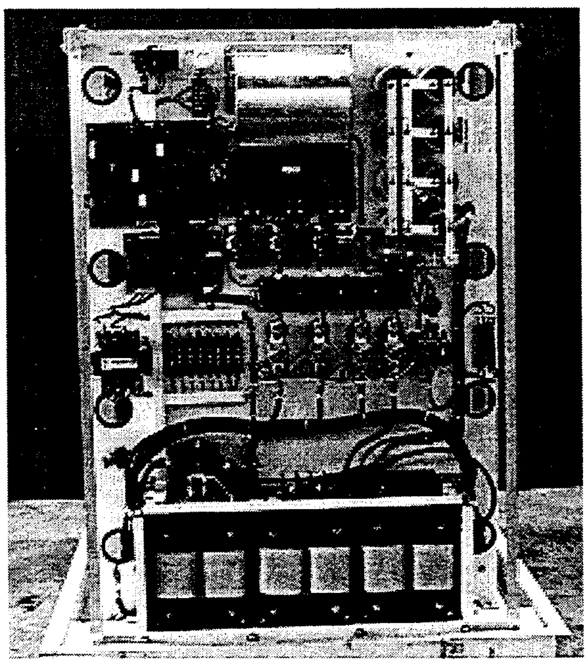

Figure 3-10. PCS Panel Mounted on Module Frame.

Estimates for PCS, transformer, and module efficiencies (exclusive of HVAC and other auxiliary loads) are measured at their respective input and output terminals and are provided below for operation at nominal-rated input and output voltages:

	Estimated Efficiency		
% Output	PCS	Transformer	Module
25	96.2%	94.5%	90.9%
50	97.6%	95.6%	93.3%
75	98.0%	96.0%	94.1%
100	98.1%	96.2%	94.4%

3.3.5 PCS Protection Features

The PCS includes appropriate self-protective and self-diagnostic features to protect itself and the module from damage in the event of a PCS component failure or from parameters beyond the PCS's safe operating range due to internal or external causes (see Figure 3-11). The self-protective features do not allow signals from the serial port to cause the PCS to be operated in a manner that may be unsafe or damaging.

The PCS, when operating in parallel with the utility service, is capable of interrupting line-to-line fault currents and line-to-ground fault currents. Faults due to malfunctions within the PCS are cleared by the PCS-protective devices and not by the container-protection device.

A temperature sensor is attached to the bridge heat sink within the PCS. The PCS actuates an alarm and goes to Shutdown when the heat sink temperature reaches 90°C.

In the event of control logic trouble or detection of excessive battery DC ground current, the PCS will also alarm and go to Shutdown. The alarm trip level is field-adjustable from 10–100 mA DC.

Two forms of protection are present in the event of a ground fault. The first is the Shutdown mode, where the batteries are isolated from the grounded utility grid. The second form of protection resides in the use of at least three fusible links in the battery string. In the event that the battery string voltage goes below 504 VDC (10.5 V/battery), the system will go to the standby mode.

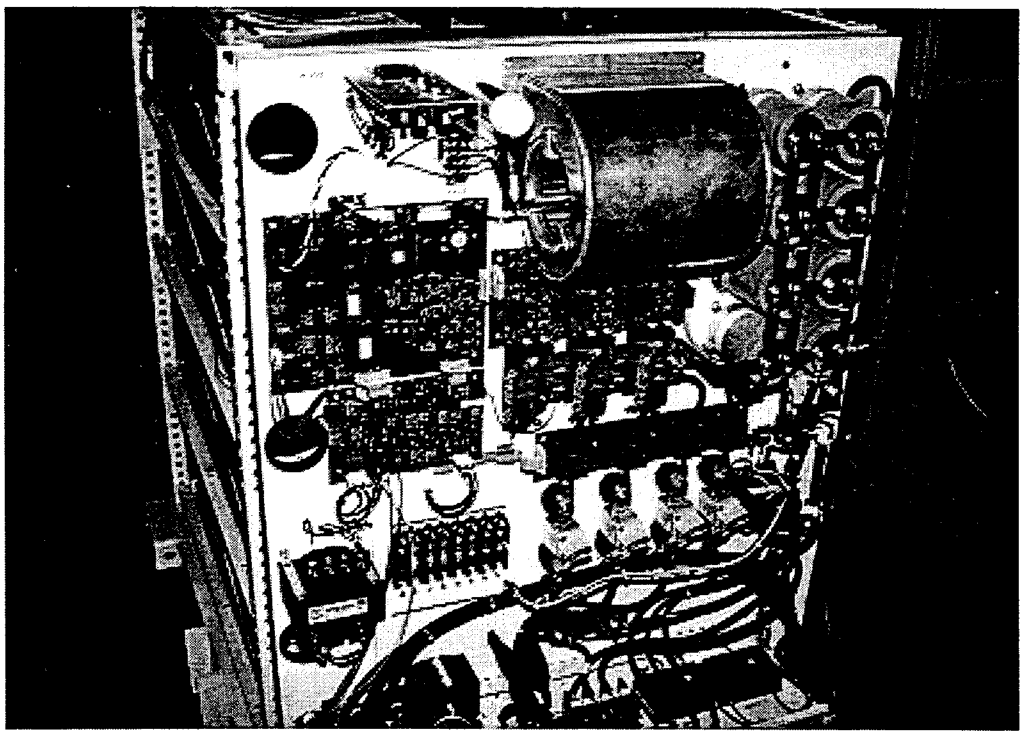

Figure 3-11. PCS Bridge Assembly.

3.3.6 Data Collection

The following quantities are measured by each PCS:

(1) String DC voltage

(2) Voltage difference between upper- and lower-string halves

(3) A Phase AC voltage

(4) B Phase AC voltage

(5) C Phase AC voltage

(6) DC current

(7) DC ground fault current

(8) Battery temperature

3.3.7 Construction

PCS wiring is bundled, laced, or otherwise laid in an orderly manner. Wiring, devices, and test points are permanently labeled or color-coded to be easily identifiable for maintenance. The PCS internal wiring has flame-retardant insulation—PVC is not used. Wires are of sufficient length to preclude mechanical stress on terminals. Wiring around hinged panels or doors is extra flexible and includes loops to prevent mechanical stress or fatigue. The PCS includes ground lugs for equipment grounding.

All exposed surfaces of ferrous parts are thoroughly cleaned, primed, and painted or otherwise suitably protected to survive for the 20-yr design life of the system.

3.4 System Control

Connections to the container consist of a 250-kVA, 480-VAC 3-phase service drop and connections to a SCADA system. Where multiple containers exist at a site, the SCADA system is connected to the first container only. The additional containers are then controlled by the first container. This makes the first container a master and the additional containers slaves. All containers have the capability of being masters or slaves as necessary. The system electrical termination panel is shown in Figure 3-12.

A 486SX/25 computer with keyboard and software is provided with this system. This computer features 4 MB of random-access memory (RAM), a 120-MB hard drive, and an accelerated video graphics adapter for a video graphics array (VGA) monitor (not included). A user-supplied VGA monitor may be installed, if desired.

Control of the container is accomplished by actions from within the container or by a SCADA system. The performance data that comes from the modules is accessible by modem on the prototype container. No control is permitted via this modem.

3.4.1 Control System Protective Functions

(1) Under/overvoltage

(2) Under/overfrequency

(3) Overcurrent protection is included within the modules.

In addition to protection included within the modules, a 50-A branch circuit breaker will be used for each of the eight modules. A 20-A fused disconnect will be used on the primary of the auxiliary transformer. Separate branch circuit breakers will be used on the secondary of the transformer to protect the HVAC, control power, and maintenance outlet circuits.

3.4.2 Data Acquisition and Control

After many hours and considerable effort spent attempting to debug the system software, a painful decision was made to revise the approach to take advantage of the SCADA software developed by PG&E. The decision was precipitated, in part, by the problems encountered when debugging the Omnion personal computer (PC)-based software, and also, in part, by the advantages of simplifying and streamlining the software. Had the use of SCADA software been anticipated at the beginning of the project, and had the full capabilities of the SCADA software been understood, this approach would have been incorporated from the very beginning of the development.

The new system software was specified in conjunction with PG&E's personnel to fully use the features inherent in the PG&E SCADA software. Based on the specification, Omnion wrote new system software and resumed factory testing. At the time of development, SCADA systems were being employed increasingly by utilities to control and monitor both generation and transmission and distribution (T&D) operations. Omnion's decision to take this approach places this project in step with progressive utility practices.

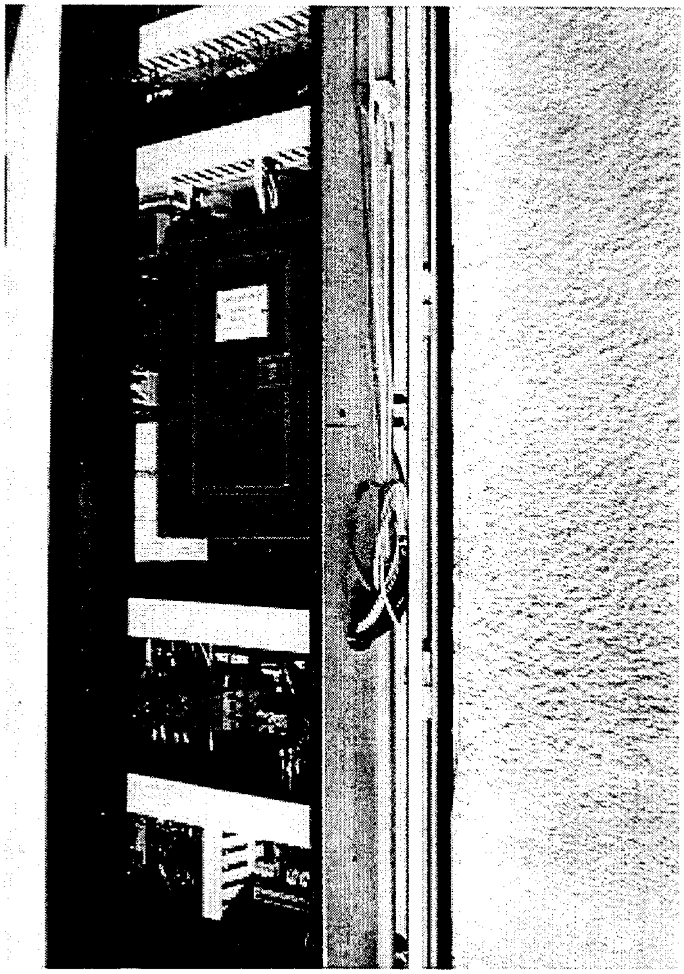

Figure 3-12. System Electrical Termination Panel.

Data are collected from modules and stored by the container data acquisition system. These data are available on modem. The following parameters are collected from each module:

(1) String DC voltage

(2) Voltage difference between upper- and lower-string halves

(3) A Phase AC voltage

(4) B Phase AC voltage

(5) C Phase AC voltage

(6) DC current

(7) DC ground current

(8) Battery temperature

Container data are also collected and stored by the data acquisition system. These data are available by modem and consist of:

(1) Power factor

(2) kW

(3) kVAR

(4) Volts AC

(5) Amps AC

(6) SOC (calculated)

(7) HVAC status

(8) Internal temperature(s) monitored by HVAC

(9) Any problems that have been reported

3.4.3 Intensive Prototype Monitoring Study

Monitoring and analysis of the 250-kW AC Battery performance variables were of keen interest to all involved in an intensive prototype monitoring study. The objective of the study was to monitor two of the eight modules in the 250-kW AC Battery container to determine how system operation affects individual batteries within the modules. Individual batteries were studied to see if their behavior differed from the behavior of an entire battery string. In addition, the thermal performance of the module and container was studied and recorded.

To better understand the electrical performance of individual batteries, the module string current and individual battery voltages were monitored. To monitor the battery thermal performance, air temperature entering and exiting the module in several places was observed and the temperature of several batteries measured directly. PCS thermal performance was studied by measuring the temperature of the bridge heatsink and one transformer.

A data acquisition system based on a Westronic D20 Remote Terminal Unit (RTU) was built and installed in the AC Battery container. Sensors were located in the container with various transducers attached to various components within the container. The other components of the system were housed within three cabinets mounted on the outside of the container. Sensor transducer signals fed into the Westronic D20 RTU were linked via RS-232 to the PG&E Master Station running PC SCADA using a PG&E protocol. The master station then polled the RTU for data and recorded them in a real-time database. Windows-based software averaged and summarized the data, and then wrote them to a structured query language (SQL) database server on the PG&E local area network (LAN).

The following information was collected and recorded for each of two modules at fixed time intervals. The numbers at the right of each category are the quantity of data points.

(1) Battery voltage (96)
(2) Battery string current (2)
(3) Battery temperature (16)
(4) Module inlet air temperature (2)
(5) Module outlet air temperature (4)
(6) PCS temperature (6)
(7) Manifold hydrogen concentration (2)
(8) Time of day
(9) Date

In addition to the above items recorded for two modules, the following data were recorded for the container.

(1) Three individual battery voltages in each of the six remaining modules (18)
(2) Container temperature (6)
(3) Outdoor temperature (1)
(4) Auxiliary power usage (1)

The system also calculated and logged the following information.

(1) Module kW (8)
(2) Module kVAR (8)
(3) Module status (8)
(4) Module ground resistor voltage (8)
(5) Module PCS bridge temperature (8)
(6) Module DC current (8)
(7) System kW
(8) System kVAR
(9) System AC voltage
(10) System AC current (3 phases)
(11) System status

Windows-based software running on the PG&E master station collected and averaged the data. For each cycle, a summary containing the information listed below was generated.

(1) DOD for the cycle (module)
(2) Discharge time (module)
(3) Discharge amp-hours (module)
(4) End-of-discharge voltage (module)
(5) Lowest battery voltage at end of discharge*
(6) Highest battery voltage at end of discharge*

*Lowest and highest of the voltages monitored in each of the two intensively monitored modules.

(7) End-of-discharge current

(8) Charge time

(9) Charge amp-hours

(10) End-of-charge string voltage

(11) End-of-charge minimum battery voltage

(12) End-of-charge maximum battery voltage

(13) Time-to-voltage limit

(14) End-of-charge current

(15) Percent recharge (Ah in/Ah out)

(16) Maximum temperature during cycle

(17) Minimum temperature during cycle

3.4.4 Remote Control

Remote control—The SCADA uses the PG&E protocol (research and development [R&D] Division). This control is not accessible using the data acquisition modem. The SCADA is capable of controlling the following parameters:

(1) Power factor

(2) Output kVA

(3) kW

(4) kVAR

(5) Automatic AC bus regulation (voltage)

(6) Operating Modes:

- Shutdown
- Standby
- Charge
- Discharge
- Schedule (Example: 100-kW discharge at 2:00 p.m. for 2 hours, recharge at 1:00 a.m.)

3.4.5 Container Electrical

A 250-kVA disconnect device with visible breaks is provided close to the service entrance. Each module has its own circuit breaker housed in a common load center. The system electrical control panel is shown in Figure 3-13.

3.5 System Safety Concerns

3.5.1 Container Mechanical

5-g Load Design: The containers and modules are designed to handle 5 g's in all directions. This value was chosen to allow transportation on a truck. Framing in the container and module has also been analyzed to keep stress below the yield point on all members. A finite element analysis was conducted by SNL on the container and revealed high stress levels in the corner posts of the container at the upper end of the structural member used to reinforce the posts. While a catastrophic failure would have been extremely unlikely, an inadequate safety factor could have resulted in local deformation of the structure during loading or unloading of the container. The solution developed was a stiffening crossbrace running from the upper corners of each door set to the lower opposite corner in the middle of the container.

Modules Bolted to Container: In order to handle a 5-g load between the container and module, the modules are bolted to the container frame.

12-ga Steel Exterior: The exterior of the container is 12-ga steel. This is .104-in.-thick steel and is chosen for ease of manufacturing and ruggedness. Exterior walls are smooth and do not offer hand- or footholds, with the exception of the handles on the doors.

Acoustical Foam: 1-in. of acoustical foam is applied to the interior surface of the container. Two functions are served by the foam: noise damping and thermal insulation.

Door Latches: Three-point stainless-steel-pad lockable door latches are used on the main doors. These latches are weatherproof and allow user-installed padlocks to be installed to keep unauthorized personnel out of the container.

Belfer Ports: Four Belfer ports were added to permit access to the module bays for fire control without opening the doors. The ports are located about 4 ft from the base of each outboard bay door. The port covers are held in place with two bolts—one bolt acting as a hinge about which the port cover is designed to rotate or swivel and the

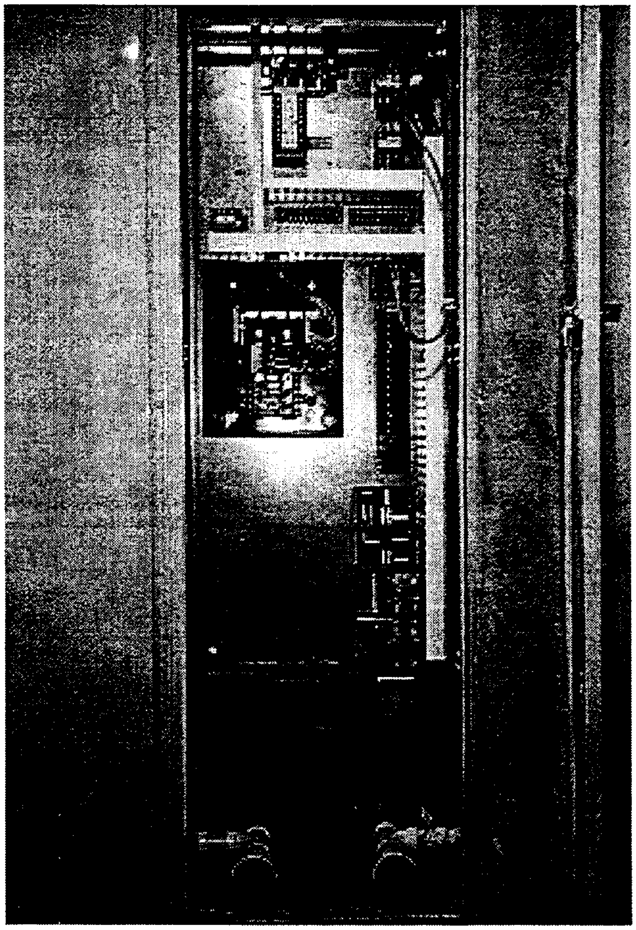

Figure 3-13. System Electrical Control Panel.

other bolt used to latch and clamp the cover firmly in place to effect a weatherproof seal. The access port is 3 in. in diameter and large enough to accommodate nozzles of common fire fighting equipment.

3.5.2 Module Mechanical

Module Covering: Yellow corrugated plastic is used around the sides and tops of the modules. This keeps people and fingers out of the batteries, and the yellow color is a natural caution sign. On the end of the module opposite the PCS, a screen allows airflow across the batteries while keeping a barrier between the high DC voltage and people who may be working around the module. The PCS is covered by thin sheet steel.

3.5.3 Container Electrical

Door Switches: Each of the four main doors has a door switch that will shut the container down if a door is opened. The door switches are designed so the system can be worked on with the doors open by pulling out the door switches, but when the door is closed the switch is again active.

Emergency Stop: Emergency stop buttons are located on the inside of the enclosure to allow workers to shut down the system. Each module has a hard-wired emergency stop provision that will open the AC contactor overriding the computer control with a hardware backup.

Smoke Detector: A smoke detector is located at the top of each container and is set up to shut down all the modules in the event that smoke is detected in the enclosure.

Hydrogen Detector: A hydrogen detector is located at the top of each enclosure to shut down the container before an explosive amount of hydrogen can accumulate.

Hydrogen Vent System: A vent system for hydrogen is discussed below. The blower on the hydrogen vent is equipped with a Hall-effect sensor that sends out a pulse on every revolution of the blower. This pulse is monitored by the control computer to verify that the blower is operating when it is turned on. If the blower fails, the container will shut down.

Container Temperature: Temperature inside the container will be monitored by the container computer. If the internal temperature of the container is too cold or hot, the container will shut down and wait until the temperature is in bounds again.

Circuit Breakers: Individual circuit breakers are provided for each module within the container. This allows isolation of individual modules, in addition to providing overcurrent protection for the wires going to each module. The fuses within each PCS are fast enough that an overcurrent at the PCS would clear PCS fuses before a circuit breaker would clear.

3.5.4 Module Electrical

DC Voltage: DC voltage is monitored by looking at the total battery string, the DC voltage, and the voltage from the +DC to the center of the capacitors. On the total DC, the voltage is compared to the maximum (816 VDC) and minimum (504 VDC) voltages allowable for the battery string. In the event that a limit is reached, the system will shut down.

Capacitor center voltage is monitored to see how far it is from the center of the total DC bus. This voltage becomes an error signal that is used to slightly shift the three-reference current waveforms to maintain a centered capacitor voltage. This is intended to adjust for any offset problems with the Hall-effect current transducers.

DC Ground Fault: An 11-ohm resistor is tied between the center of the battery and the center of the capacitors. This resistor performs two functions: monitoring ground-fault currents and looking for weak batteries in the string. A voltage reading across the resistor can indicate either. To distinguish between a ground fault and a weak battery string, the PCS can be shut off. With the ground resistor connected, only ground current will flow.

DC Injection: Omnion used a transformerless topology for the PCS in the AC Battery system. The disadvantage of this topology is that it is possible to inject DC into the output transformer. This could occur if there is a control failure of some sort. To trap this type of failure, the PCS monitors output current, filters out the 60 Hz, and looks for small DC signals. If DC is present, the system will shut down.

Overcurrent: A Hall-effect current transducer is used to sense the DC current between the DC capacitors and the IGBTs. This will detect any overcurrent condition, both AC and DC.

AC Voltage: AC voltage is monitored by taking the voltage at the output of the converter, stepping it down with a small, high-frequency (5,000 Hz) filter, and converting it to a DC value proportional to the root mean square (RMS) of the AC voltage. This value is sent to the master control for processing into over- and undervoltage values with appropriate delays. In the event of an over- or undervoltage on any of the three phases, the system will shut down.

AC Frequency: When the AC voltage waveform is processed to get the magnitude information, it is also processed into square waves. These square waves are used for several things. The "A" phase square wave is adjusted for a fixed delay and converted into a pulse that is used to measure frequency. Frequency is measured each cycle. Over- and underfrequency are calculated based on frequency set points and the number of cycle delays in software. If over- or underfrequency are detected, the system will shut down.

AC Rotation: Direction of rotation of the three phases is obtained by comparing the square waves generated by the "B" and "C" phases to the "A" phase interrupt. Rotation can be forward or reverse, with the PCS control adjusting the rotation direction to match the connection.

Islanding Protection: The AC Battery PCS is a current source converter that puts out a current waveform. If the utility voltage is lost, the voltage will drop rapidly if the load at the output of the PCS is higher than its output. If the load at the output of the PCS is lower than the output, the voltage will go up. The most difficult condition is when the load matches the output of the PCS. To protect against an island in this condition, the PCS is synchronized to the utility using a phase-lock-loop. The free-running frequency of the phase-lock-loop is constantly changed to force an over- or underfrequency trip in the event that a balanced load exists on the output terminals of the PCS.

Synchronization Failure: On each cycle, the phase-lock-loop is checked to verify that synchronization between the utility and the output of the phase-lock-loop exists. If the lock is lost, the system will shut down. It will remain in Shutdown mode until the system can verify that a lock exists for several seconds, and then it will continue operation.

Blown Fuse: Within the PCS, six fuses protect all three phase outputs and the DC bus before and after the DC bus capacitors. Each of these fuses has a switch that will tell the PCS that a blown fuse exists. This will shut down and disable the PCS.

Power Supply Monitors: The master control board has detectors that monitor the +15 and -15 V power supplies. If either of these go below approximately 14.4 V, the system will shut down. In addition, the watchdog timer chip on the master control monitors the +5 V signal and shuts down the system if the +5 V signal goes below 4.2 V.

Fiber-Optic Serial Port: All communications between the container computer and the module occur over a fiber-optic serial port. This communication is checked in several ways. Each transmission is done in a 6-byte package with the last byte being a checksum. If the 6 bytes are added together, they must be divisible by 256 with no remainder. If they are not, an error is generated and the command is ignored. Additionally, there are a small number of commands that are given to the module. If a command is sent that is not part of the known commands, the PCS will ignore the command and set a flag to show that a bad command has occurred. Finally, the information coming over the fiber-optic link is done on a continual basis. If there is no communication for 1 sec, the PCS assumes that it lost its link to the main computer and shuts down.

Battery Temperature: A thermocouple is attached to one of the batteries in the middle of the string. This is used to monitor battery temperature and cycle the PCS blower to keep the battery case temperature within the specified 60-90°F range. If the battery temperature goes out of this range, the system shuts down until the battery temperature is within its limits again.

PCS Temperature: A second thermocouple is attached to the case of the "B" phase IGBT. This is used to monitor the IGBT temperature, turn the PCS blower on, and shut down the system if the IGBT gets too hot.

Open Thermocouple: An alarm circuit will shut down the system if either thermocouple fails in the open condition.

3.5.5 Container Chemical

Acid Reservoir: The container has a reservoir between the bottom of the container and the container frame. This reservoir is created by spraying a coating of 15 mils of ethylene methacrylic acid copolymer on the bottom of the container frame. The reservoir will hold 106 gallons of sulfuric acid (16.4% of the total acid in all the batteries in the container).

Hydrogen Venting: Hydrogen generated during charging is collected in a network of tubing that runs from each battery in every module to one of four 2-in. PVC pipes running vertically in each container (see Figure 3-14). These pipes are open to the outside at the bottom of each pipe and are connected to a common plenum equipped with a blower that pulls air through the pipes and exhausts it through a vent in the roof of the container (see Figure 3-15). The blower is sized to maintain the concentration of hydrogen in the pipes below 2% at all times. Use of the blower causes the pipes to run at a negative pressure relative to the interior of the container. In addition to the blower, the vertical orientation of the pipes provides a natural path for hydrogen to escape to the atmosphere.

3.5.6 Module Chemical

Battery Base: Each battery rests on a base made of pultruded fiberglass. This material was selected for its strength, low cost, and chemical resistance.

Battery Tie Down: Batteries are tied to the Module trays by putting a pultruded "C" channel over the batteries and using stainless-steel bolts on each side of each battery to hold the batteries down. Stainless-steel hardware is used to tighten the bolts.

A Production Cost Estimate for the AC Battery system is provided in Appendix H.

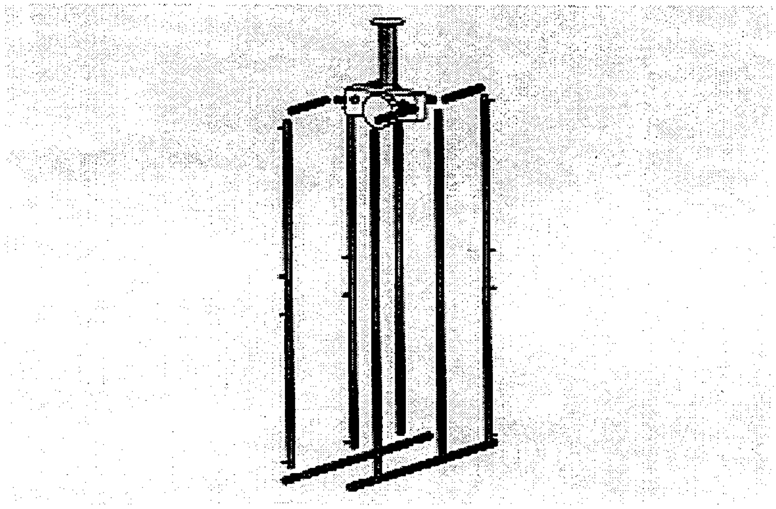

Figure 3-14. Hydrogen Gas Forced-Air Exhaust System Piping.

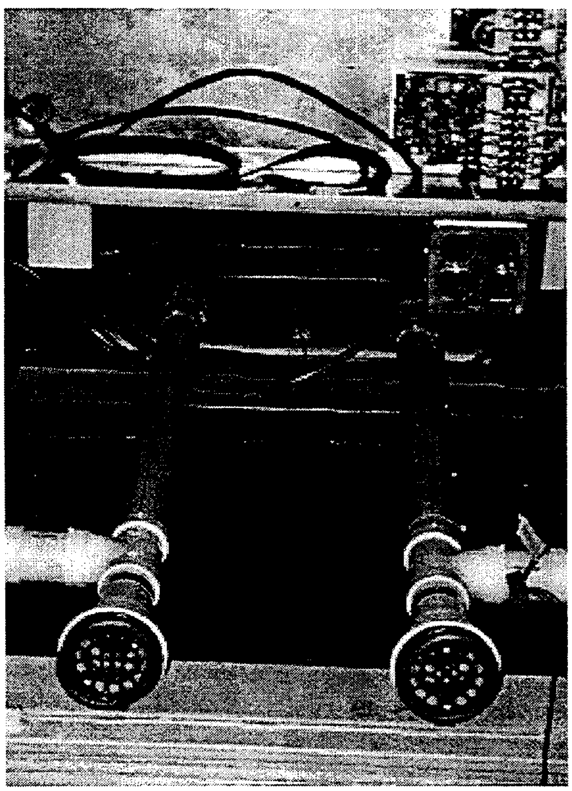

Figure 3-15. Hydrogen Gas Forced-Air Exhaust System Intakes.

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4. Maintenance

The installation, adjustment, or repair of this equipment involves the risk of contact with potentially lethal voltages and currents. No attempt to install or service this equipment should be made by anyone who is not a qualified, trained technician familiar with power electronic equipment.

Potentially lethal DC voltages are present in the modules, even after AC power is removed. Module servicing by the user is not recommended.

It is essential that the two hydrogen sensors be checked for calibration at regular intervals. The sensors are located in the center electrical control cabinet area on bulkheads near the top of the container. Calibration checks should be done on a monthly basis for the first several months. If sensors remain accurate within 3% without adjustment for a 2-month period, then the calibration interval can be increased to bimonthly.

The remainder of the system components do not require any routine maintenance. It is recommended that calibration checks encompassing the procedures in the Operations and Maintenance (O&M) Manual be conducted to verify overall system accuracy. When calibrating, remember that high DC voltages exist between battery voltage channels and that the RTU and +5 and +24 VDC power supplies are powered with 120 VAC.

The only other routine maintenance is associated with the replacement of batteries at the end of their service life.

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5. Factory Testing

Final factory testing of the AC Battery was delayed and limited in scope due to difficulties in debugging system software. A decision was made in late September 1993 to use the PG&E SCADA software. On October 14, 1993, a preshipment baseline test was performed and the AC Battery system was prepared and shipped the following day to PG&E. Omnion concluded system testing on site (see Figure 5-1) in conjunction with startup at the PG&E test facility. The AC Battery Test Plan is available upon request.

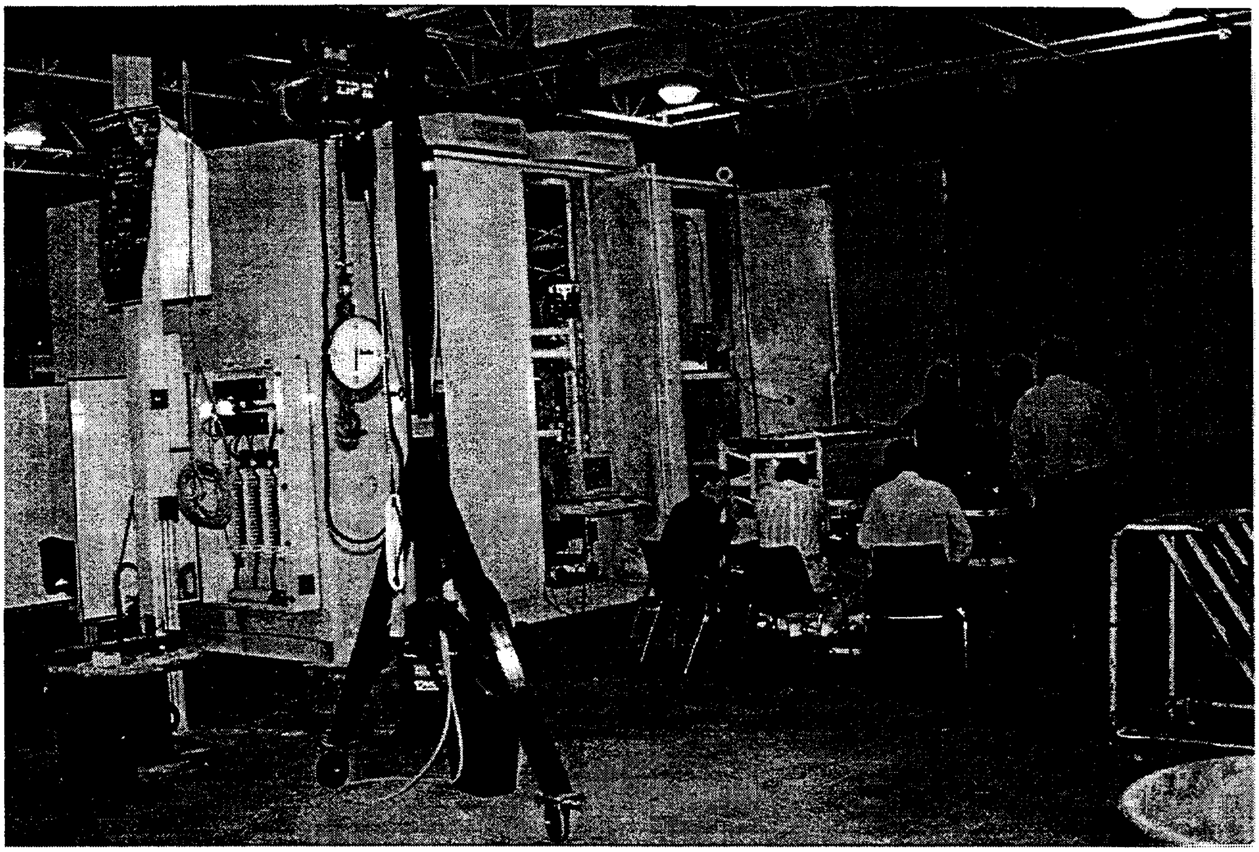

Figure 5-1. Factory Witness Testing.

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6. Field Startup and Operation

PG&E installed the AC Battery system in the "Smart Substation" adjacent to the Modular Generation Test Facility (MGTF) at San Ramon, California. High-voltage transformation, switchgear, and protection were provided by PG&E. Figure 6-1 shows the container mounting pad. Figure 6-2 shows the AC Battery system being mounted on the pad. All control and data acquisition were performed through the SCADA system. Copies of the PG&E AC Battery Test Plan (Generation and Storage Report 007.5.93.6) and Test Report (Customer Systems Report 007.5-94.14) are available upon request.

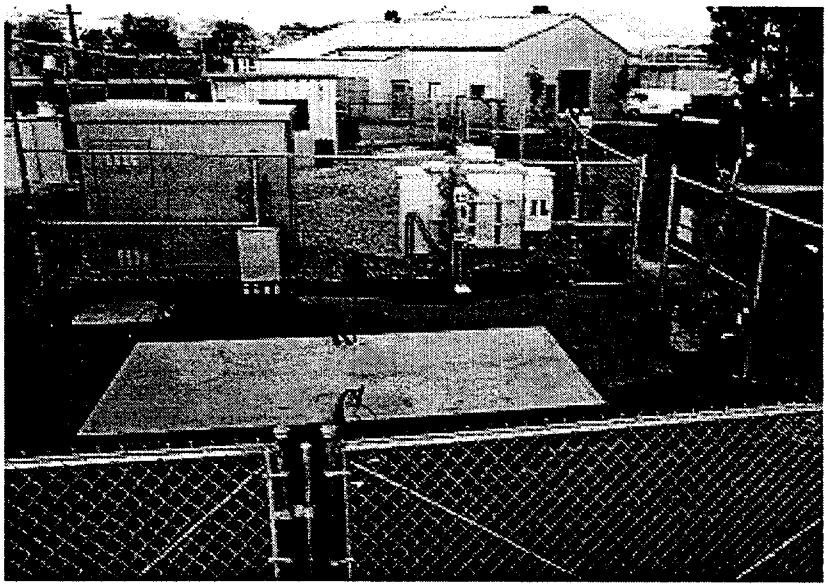

Figure 6-1. Container Mounting Pad.

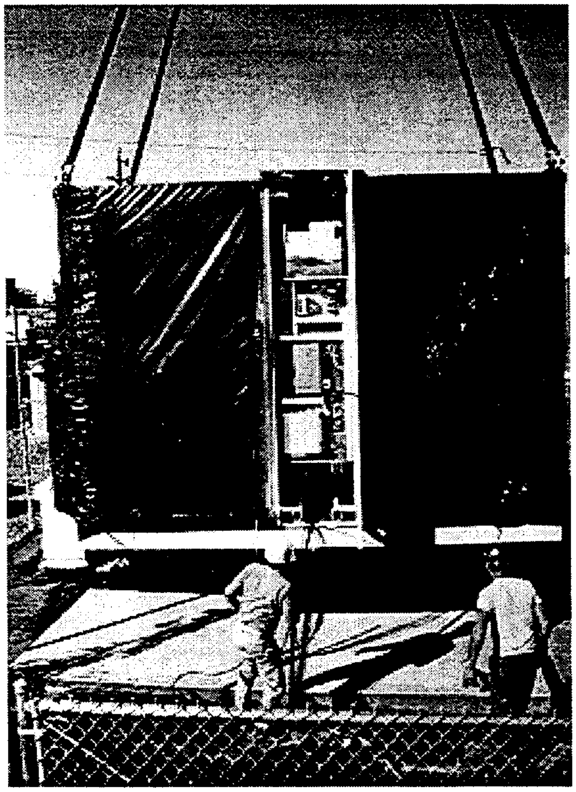

Figure 6-2. Mounting the AC Battery System on Its Pad.

7. Summary and Conclusions

The AC Battery concept was successfully developed and tested in a cooperative government, utility, and industry project. Figure 7-1 shows the test setup for the PM250 at the PG&E MGTF.

The AC Battery system demonstrated that:

(1) The concept of manufacturing modular, factory-assembled, containerized systems may enhance product and system reliability.

(2) Complete factory assembly reduces on-site start-up time and cost.

(3) Power output of the container is high-quality and well within the applicable Institute of Electrical and Electronics Engineers (IEEE)-recommended limits for harmonic content.

(4) Remote dispatchability of battery storage systems is practical.

(5) A BESS, when operated in the current-source mode, can meet several utility-scale applications.

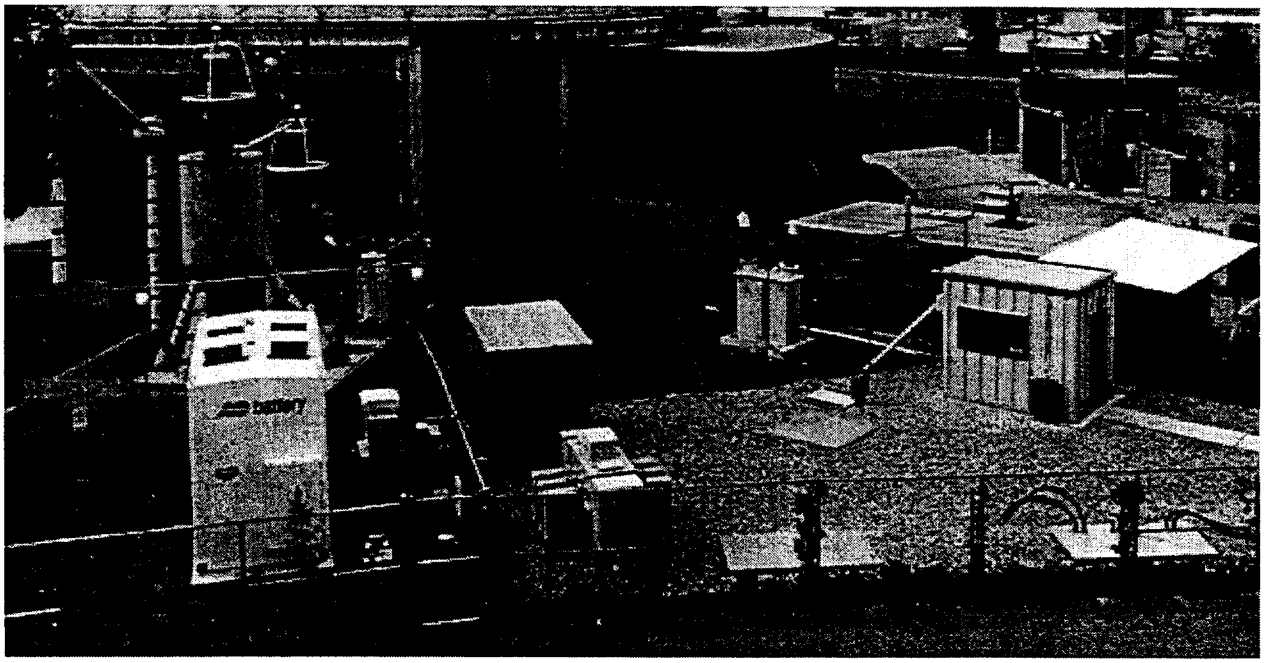

Figure 7-1. AC Battery PM250 Test Setup at PG&E MGTF.

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A

Initial Design Assumptions

Appendix A
Initial Design Assumptions

Introduction

In the initial stage of design development, a set of preliminary design specifications and a description of operation were developed. These preliminary design specifications were based on inputs described in the Introduction as well as a number of assumptions that are outlined below. As the development process progressed, the design took form and matured. The list below is offered to explain the rationale used in formulating the original design specifications.

System Capacity

(1) The system was rated at 500 kW to make it a meaningful size for utility applications.

(2) The system was rated at 500 kWh to provide a nominal 1-hr rating. The current rating of the proposed battery required that 864 batteries be used to obtain a 500-kWh system rating if operated at 250 kW for 2 hr. Another consideration was using 1,152 batteries to achieve a 500-kWh rating for 1 hr.

Container Transportability and Design

(1) Truckable height was set at 13.5 ft to meet requirements in most states.

(2) Gross truckable width was set at 8.5 ft. The first level of permitting is from 8.5–10 ft and is fairly simple. All that is involved is getting the permits and attaching a "Wide Load" sign. The permits from Wisconsin to California cost about $500. Beyond 10 ft, the requirements are cost-prohibitive, involving chase and lead cars.

(3) Truckable weight was set at 80,000 lbs. This could be increased to 100,000 lbs if the item being trucked cannot be separated into smaller components. Fortunately, the modules are easily removed and trucked separately.

(4) An empty truck with a steel trailer weighs 40,000 lbs. An empty truck with an aluminum trailer weighs 36,000 lbs. This leaves 40,000–44,000 lbs for the load.

Module

(1) The cost of power conversion is minimized by minimizing the number of converters where each converter uses a single three-phase bridge.

(2) Using a 1,200-V insulated gate bipolar transistor (IGBT) gives a maximum operating DC voltage of about 800 VDC. If current is low during times of high voltage, this value can be increased somewhat.

(3) The minimum DC voltage per battery will be 10.5 VDC.

(4) A maximum voltage per battery of 17.0 VDC is required.

Power Conversion System

(1) The power conversion should be similar to the existing Omnion 3200 series converter.

(2) The design should attempt to minimize the cost of the inductors. This can be done by taking advantage of skewing the output of many modules. With a skewing regulator, high-frequency ripple current is canceled by other bridges allowing either lower inductance, lower-frequency operation (higher efficiency), or both.

(3) Module software should be capable of being changed from the container. This can be accomplished by using flash or static random-access memory (RAM).

(4) DC bus capacitance will be a split bank of 450-VDC capacitors.

(5) The DC voltage will range from 378 (10.5 × 36) to 612 VDC (17 × 36).

System Electrical Control

(1) Control of the container shall be accomplished by actions from within the container or by a system control and data acquisition (SCADA) system that is totally separate from the modem in Assumption 2 (below).

(2) The performance data that come from the modules should be accessible by modem on the first container. No control is permitted via this modem.

(3) The equipment shall meet the requirements of the Pacific Gas & Electric (PG&E) Power Producer's Interconnection Handbook where the requirements can be met at the 480-V output connection. Any protective relaying equipment (e.g., a transformer ground fault relay) required on the utility side of a utility-supplied transformer shall be supplied by the utility.

Initial System Description and Specifications

The following initial system overview and specifications are provided to present the starting point for concept development and a description of the evolution of the product design. As all designs require trade-offs, explanation is provided to assist with an understanding of the design development process.

System Container

The initial design concept (see Figure A-1) called for a containerized, pad- or pier-mounted outdoor enclosure that would house the modules; switchgear; and the heating, venting, and cooling (HVAC) and SCADA systems. The container must be capable of automatic operation in any ambient condition while maintaining internal operating temperature within a narrow band that optimizes battery performance. The container should be designed for operation in open spaces while maintaining operating temperatures inside to allow the operation of the modules within the temperature limits established in Task 2 of the SNL Statement of Work (SOW). The container will also include electrical service panels, a system controller, and environmental controls.

System Description

The container was originally designed to house 36 modules in a configuration that occupies the least volumetric space inside the container, while preserving electrical isolation between individual modules and allowing access for servicing of all modules and equipment contained within them. The container should be transportable via truck to the customer's installation site.

The size and weight of the container must be within allowable limits for shipment by truck. The approximate size of the container will be 26 ft long, 9 ft wide, and 12 ft high. The target weight of the container, complete with 36 modules, must not exceed 72,000 lbs.

Electrical Characteristics

(1) Input/Output Voltage: 480 VAC, 3-phase.

(2) Frequency: 60 Hz.

(3) Current THD: < 5%.

(4) Power Factor: Unity/controllable (charge and discharge).

(5) Energy Capacity: 500 kWh at 2-hr rate to 80% depth of discharge (DOD) using a minimum of 864 batteries in 18 modules (the number of modules and batteries per module may vary).

(6) Maximum Power: The maximum power output of the container will be 500 kW.

Physical Characteristics

(1) Size: Maximum 40'L × 10'W × 9.5'H.

(2) Weight: 80,000 lbs gross (maximum).

(3) Shock and vibration resistant to 5 g's.

(4) Foundation load-bearing capacity of 375 lbs/ft^2.

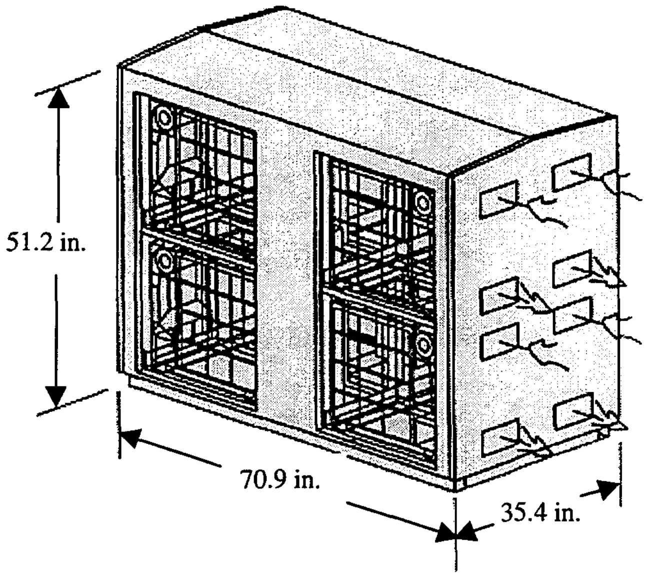

Figure A-1. Initial System Container Design Showing Airflow Patterns.

(5) Minimum spacing of 10 ft is required on both sides of the container for servicing of the modules.

Construction

(1) Welded structural/sheet steel and composite construction.

(2) Access for battery installation and service via hinged doors.

(3) Access for HVAC, power connections, data acquisition hardware, and system control.

(4) Subframe suitable for transportation by truck.

(5) Vandal-resistant exterior surfaces.

(6) Finish: White enamel interior, beige ultra-violet (UV)-resistant exterior over primer.

(7) Insulated to R-11/R-13.

Environment

(1) Ambient conditions: -20°F to 120°F with 0 to 100% humidity, rain, snow, hail, etc.

(2) HVAC provision to maintain the interior of the container at 80°F ±20°F.

(3) Air exchange to prevent hazardous gas buildup.

Safety

(1) An eyewash and shower will be provided with the container.

(2) A first aid kit will be provided with each container.

(3) A basic powder for neutralizing acid spills will be provided.

(4) Fire extinguishers will be provided.

(5) The container will conform to the National Electric Safety Code.

(6) A hydrogen sensor will be provided to turn off the container in the event that hydrogen gas in excess of 1% is detected inside the container.

(7) A smoke detector will be provided to turn off the container in the event that smoke is detected inside the container.

Transport

(1) Container with partial load of battery modules in place will ship on a normal flatbed semitrailer requiring over-width permit only.

(2) Approximately 40,000 lbs of batteries will be shipped in a second (enclosed) semitrailer.

Handling

(1) Loading and unloading of the container will be accomplished with a system of rails and jacks to be developed and will not require an outside contractor.

(2) Batteries shipped in an enclosed truck will require the use of a forklift for transfer to the container.

System Control

Protective Functions

(1) A circuit breaker for the full 500 kVA will be provided. The breaker will have a shunt trip that can be activated by protective relays as required.

(2) Overvoltage protection using a device approved by PG&E will be provided.

(3) Undervoltage protection using a device approved by PG&E will be provided.

(4) Over- and under-frequency protection, using a PG&E-approved device, will be provided.

(5) Voltage-restraint/voltage-controlled over-current relays will be provided for each phase.

Service Entrance

(1) The utility service entrance into the container will conform to PG&E's Service Book (the "Green Book").

Data Acquisition

(1) Data will be collected from modules and stored by the container data acquisition system. These data will be available on modem. The following parameters will be collected from all modules:
- String DC voltage
- DC current
- Battery temperature

(2) Container data will also be collected and stored by the container data acquisition system. These data will be available by modem. The following data will be collected:
- Power factor
- kW
- kVAR
- Volts
- AC
- Amps
- AC
- State of charge (calculated)
- Any problems that have been reported

Remote Control

(1) Remote control—SCADA using PG&E protocol (research and development [R&D] Division). This control will not be accessible using the data acquisition modem. The control shall be capable of controlling the following parameters:
- Power factor
- Output kVA
- kW
- kVAR
- Automatic AC bus regulation (voltage)
- Operating mode:
  - Shutdown
  - Standby
  - Charge
  - Discharge
  - Schedule (250-kW discharge at 2:00 p.m. for 1 hr, recharge at 1:00 a.m.)

Container Electrical

(1) A disconnect device with visible breaks will be provided close to the service entrance.

(2) A transformer will be provided within the container to convert the output of the modules from 255 to 480 VAC.

(3) Each module will have its own circuit breaker housed in a common load center.

Modules

Each module will house a PCS and batteries. The following specifications are based on 48 batteries per module, which is the configuration the system ultimately had.

(1) Battery Configuration: 48 batteries, series connected

(2) Module Size: 40"H × 50"W × 41"D

(3) Module Weight: 3,600 lbs (estimated), 4,000 lbs (max)

(4) Construction: Welded/bolted steel frame

(5) Finish: Highly resistant to sulfuric acid

(6) Provision will be made in the module for easy handling with a forklift.

(7) Provisions will be made for stacking modules two high while meeting Universal Building Code Seismic Zone 4 requirements.

Input/Output Characteristics

(1) Input/Output Voltage: 255/147 VAC, 3-phase 4-wire

(2) Input/Output Frequency: 60 Hz

(3) Capacity: 28 kW/28 kWh (to 80% DOD at 2-hr rate) out of the module

(4) In addition to the four-wire power connection, up to four fiber-optic duplex connections need to be made to each module.

Battery Characteristics

(1) Battery Type: Delco 2000 with some modifications that will improve the cycle life of the battery over existing Delco 2000 batteries

(2) Battery Size: 13"L × 6.8"W × 9.5"H (Group 31)

(3) Battery weight: 60 lbs maximum

(4) Minimum Battery String Voltage: 504 VDC (10.5 V per battery)

(5) Maximum Battery String Voltage: 816 VDC (17.0 V per battery)

(6) Required Cooling/Heating Air: Sufficient to keep the air flowing across the batteries between 60°F and 100°F

Battery Module Safety

(1) Each battery string will have fuses in the positive and negative DC leads at the converter.

(2) Located in the battery string will be at least two fusible links, located between battery levels.

(3) Module construction will be such that while air can flow past the batteries, some type of protection will be provided so that live electrical parts cannot be touched.

(4) Each battery shall have its vent connected to vent tubing that will provide a path for hydrogen from the battery to the outside of the container.

Power Conversion System

System Configuration

(1) A single power conversion system (PCS) capable of delivering 28 kVA shall be supplied per module. The PCS output parameters shall be:
- Operating Voltage: 255/147 VAC ± 10%
- Number of Phases: Three
- Frequency: 60 Hz ± 1 Hz
- Nominal Operating Current: 63.4 AAC
- Maximum Operating Current: 70.4 AAC

Note: Although it was expected that the above parameters would be used, another possibility that was considered was the use of an integrated inductor transformer in which the output of the PCS would be 480/277 VAC. The transformer portion of the magnetics could be either an isolation transformer or an auto transformer.

(2) The PCS shall be self-commutated using IGBTs in a full-bridge transformerless circuit topology (with neutral connected) suitable for meeting the specifications delineated herein at low cost and with high reliability.

(3) The PCS shall be supplied in a manner that will integrate with the battery module.

(4) The output of the module shall be capable of being synchronized with other modules so that the high-frequency ripple in the output-current waveform of any one module can be canceled by other modules in the container.

Operating Characteristics

(1) Each PCS shall be capable of operation over a serial fiber-optic cable.

(2) The PCS shall include the following modes of operation:

Mode 1: Disconnect—No power at the AC terminals. The PCS has no method available to change out of this mode.

Mode 2: Shutdown—AC contactor open. Control system power shall remain energized. This condition is the result of a PCS fault or may be commanded over the serial cable.

Mode 3: Standby—AC contactor closed. Control system power energized. IGBTs not switching. System can start converting power as soon as it is commanded to convert power.

Mode 4: Run—AC contactor closed and current flowing.

(3) As a minimum, the PCS shall be able to accomplish the following functions:

(a) Shutdown—The PCS shall open its AC output contactor under the following conditions and remain in the Shutdown mode until a serial reset is initiated:

- PCS Overtemperature Indication
- Synchronization Error
- Blown Fuse
- Power Supply Fault
- DC Ground Fault
- Desat Detectors (IGBT over-current)
- Time-out on Serial Port (lost connection)
- Go to Standby Serial Command
- Shutdown Contact Closure

(b) Standby—The PCS shall have the AC contactor closed and the IGBTs not switching. This mode is reached by serial port command.

(c) Run—In this mode, the PCS shall operate normally. This mode is reached by serial port command. In this mode, the converter is given a kVA level to operate at and a power factor. In addition, each phase can be independently controlled in kVA and power factor.

Protection Features

(1) The PCS shall include appropriate self-protective and self-diagnostic features to protect itself from damage in the event of PCS component failure or from parameters beyond the PCS's safe operating range due to internal or external causes. The self-protective features shall not allow signals from the serial port to cause the PCS to be operated in a manner which may be unsafe or damaging.

(2) The PCS, when operating in parallel with the utility service, shall be capable of interrupting line-to-line fault currents and line-to-ground fault currents. Faults due to malfunctions within the PCS shall be cleared by the PCS protective devices and not by the container protection device.

(3) A temperature sensor shall be attached to the bridge heat sink within the PCS. The PCS shall alarm and go to Shutdown when an overtemperature condition is detected.

(4) The PCS shall alarm and go to Shutdown in the event of control logic trouble.

(5) The PCS shall alarm and go to Shutdown upon detection of excessive battery DC ground current. The alarm trip level shall be field adjustable from 10–100 mADC.

Note: Sensing will be accomplished by putting the positive and negative leads from the battery string through a summing Hall-effect current transducer. If a ground is present, not all the current will be flowing in the two battery leads. Additional current will flow through the ground fault, resulting in an imbalance. Two forms of protection are present in the event of a ground fault. The first is the Shutdown mode, in which the batteries are isolated from the grounded utility grid. The second form of protection resides in the use of at least two fusible links in the battery string.

(6) In the event that the battery string voltage goes below 504 VDC (10.5 V per battery), the system will go to the Standby mode.

Data Collection

(1) The following quantities shall be measured by each PCS:
- String DC Voltage
- A Phase AC Voltage
- B Phase AC Voltage
- Heat Sink Temperature
- Battery Temperature (1)

Construction

(1) PCS wiring shall be bundled, laced, or otherwise laid in an orderly manner. Wiring, devices, and test points shall be permanently labeled or color-coded to be easily identifiable for maintenance. PCS internal wiring shall have flame-retardant insulation—PVC shall not be used. Wires shall be of sufficient length to preclude mechanical stress on terminals. Wiring around hinged panels or doors shall be extra flexible and shall include loops to prevent mechanical stress or fatigue.

(2) The PCS shall include ground lugs for equipment grounding.

(3) All exposed surfaces of ferrous parts shall be thoroughly cleaned, primed, and painted or otherwise suitably protected to survive for the 20-yr design life of the system.

B

Battery Thermal Test Report

ONAN ION POWER ENGINEERING CORPORATION
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Static Power Conversion and System Control FAX 414-363-4080

AC BATTERY DEVELOPMENT

BATTERY THERMAL TEST

Document #900577
May 5, 1992

PURPOSE:

Determine room temperature ambient air flow required to prevent overheating of the batteries under the worst-case loading conditions. Worst case is expected to be frequency stabilization because this loads the battery in a steady state condition.

For this test, the battery was discharged from 100% state of charge (SOC) to 80% SOC and then recharged as follows: 8 minute discharge at 28 kWDC using a string of 47 batteries followed by 1 minute rest, 8 minute charge at 28 kWDC followed by 1 minute rest repeated for 8 hours. This routine held the battery at approximately an 80% state of charge. Battery voltages were monitored to ensure that the battery was not being discharged or charged on a cumulative basis.

PROCEDURE:

A single row of three batteries was extracted from a 47 battery string (module) and mounted in an insulated box of two inch thick styrofoam with 8x12 inch inside dimensions. The box was 48 inches long and built to represent the expected module geometry for air flow. Figure 1 shows the configuration of the test.

Ambient air was blown past the batteries by a variable speed fan. Air velocity was measured at the discharge. Temperature probes were installed at the inlet, outlet, battery post and between batteries to measure the heat dissipation and battery temperature. The between battery measurement was taken between batteries that were touching each other to attempt to get battery internal temperature. Battery string voltage and temperatures were recorded at nine minute intervals during normal working hours. Each night the batteries were brought to full charge at constant 25 amp until reaching 16 volts per battery, then constant voltage to 100% charge. The batteries were discharged to 80% SOC prior to the start of the next test the following morning.

Three levels of airflow were evaluated for five to six hours each. The air velocity recorded was through a three inch dia tube in order to obtain a reasonable velocity for the instrumentation and converted to CFM past the batteries.

The test data is shown in tables and graphs appended to this report.

RESULTS:

Heat extracted from the batteries was calculated by the formula $Q=CFM*Cp*(t2-t1)$ in BTU/min considering standard air at 68°F where $Cp=.0181$ BTU/ft^3/°F.

Air Velocity (FPM)	100	200	400
Air Flow (CFM)	4.86	9.72	19.44
Q (BTU/min)	.87	2.28	3.17
Q (WATTS/3 batts)	15	40	55.7
Q (WATTS/module)	240	640	891

OBSERVATIONS:

The battery temperature did not stabilize with 4.86 cfm air flow, barely stabilized with 9.72 and stabilized at about four hours at 19.44 cfm air flow then tracked the ambient temperature.

In each case, the battery temperature as indicated by the probe located between batteries reached about 42 deg C and recovered to about 38 deg C while on the overnight charge with no ventilation.

The charge/discharge cycle used here of five to six hours operation with slow recharge is considered to be more severe than anticipated in commercial use.

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Page 3
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CONCLUSIONS:

The total battery contribution to heating within the container is approximately 24,000 BTU/hr (891 watts*8 modules*3600/1.055) for a period of five to six hours for a daily average of 1013 BTU/hr. Considering the narrow range of ambient to discharge air temperature seen, it appears that a cooling capacity of about 12,000 BTU/hr should be adequate to maintain the ambient temperature within acceptable limits.

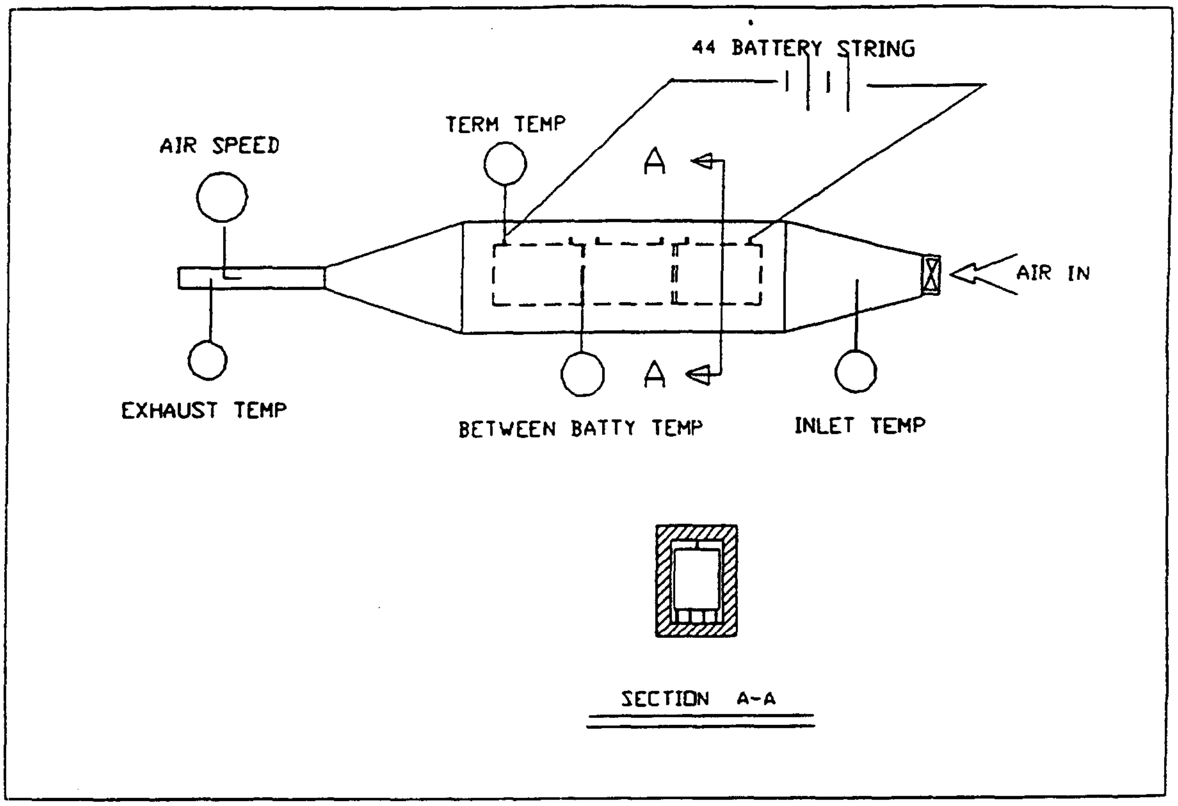


Fig. 1

Skewing Report

C

AC BATTERY DEVELOPMENT

POWER CONVERSION SKEWING MODELING

DOCUMENT #900572
April 29, 1992

David Porter
John Wanninger

INTRODUCTION

A 500 KW AC Battery is comprised of 18 modules where each module has its own converter. This paper investigates one way to use this configuration to advantage. An advantage that multiple converters has is that the outputs can be skewed, that is the high frequency component of the current waveform can be shifted from one bridge to the next.

In the past this has been done with SCR converters using two or more phase displaced bridges in parallel to get better output waveforms. Two SCR bridges in parallel give a 12 pulse output with substantially lower harmonics than one 6 pulse bridge.

In the AC battery we want to take advantage of this by phase shifting the high frequency current waveforms to cancel the high frequency component in the output waveform. If we can cancel the high frequency component, then the high frequency component can be larger. This will allow reduction in the switching frequency, the use of smaller inductors, or both.

COMPUTER MODELING

Our main goal in modeling skewed bridge outputs is to find out what effect various parameters have on the output waveform both at the output of a single module and at the output of the container. Our goal is to keep the THD (total harmonic distortion) of the current out of the container under 5%.

This has been an Omnion goal for many years and has been typical of our converters. What is different here is that, while in the past we have looked at second through fiftieth integer harmonics of 60 Hz, for this exercise we are looking at all harmonics. Since our IGBT converters have typically run at a switching frequency of 7680 Hz, looking at frequencies over 3000 Hz is more demanding.

Figure 1 shows the typical waveform that has been used in the past. The computer model used to simulate this waveform assumes a 660 VDC bus voltage, 750μH inductors, and a 7680 Hz switching frequency. While the individual switching cycles are hard to make out, the width of the switching band is readily seen.

FIGURE 1

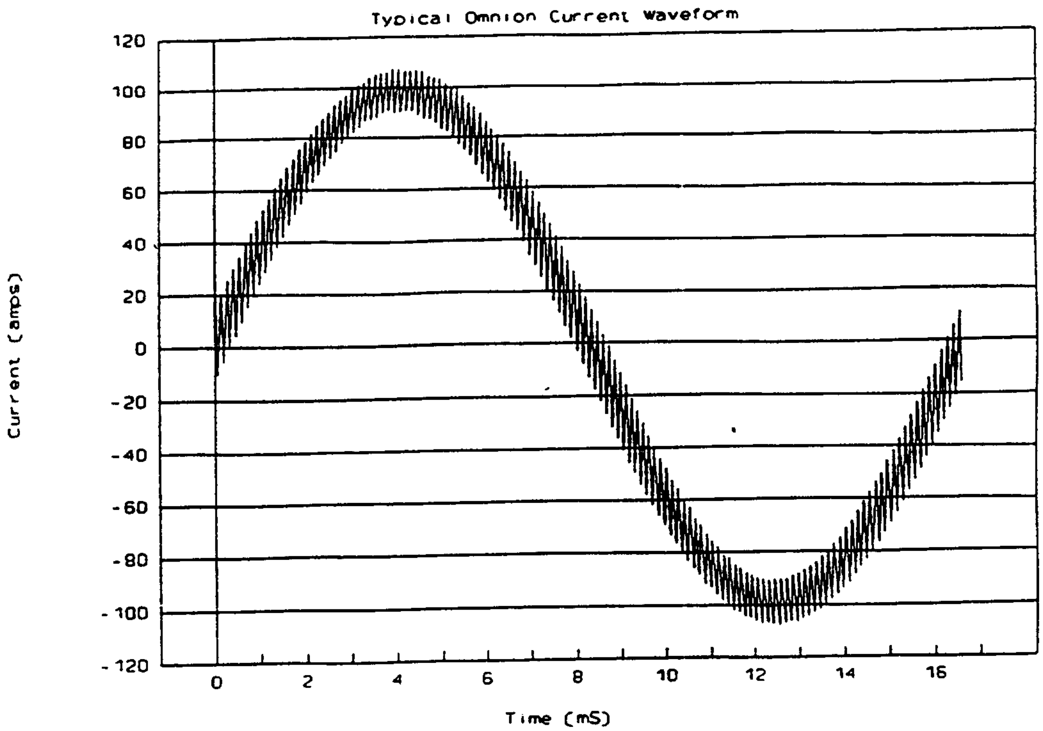


FIGURE 2

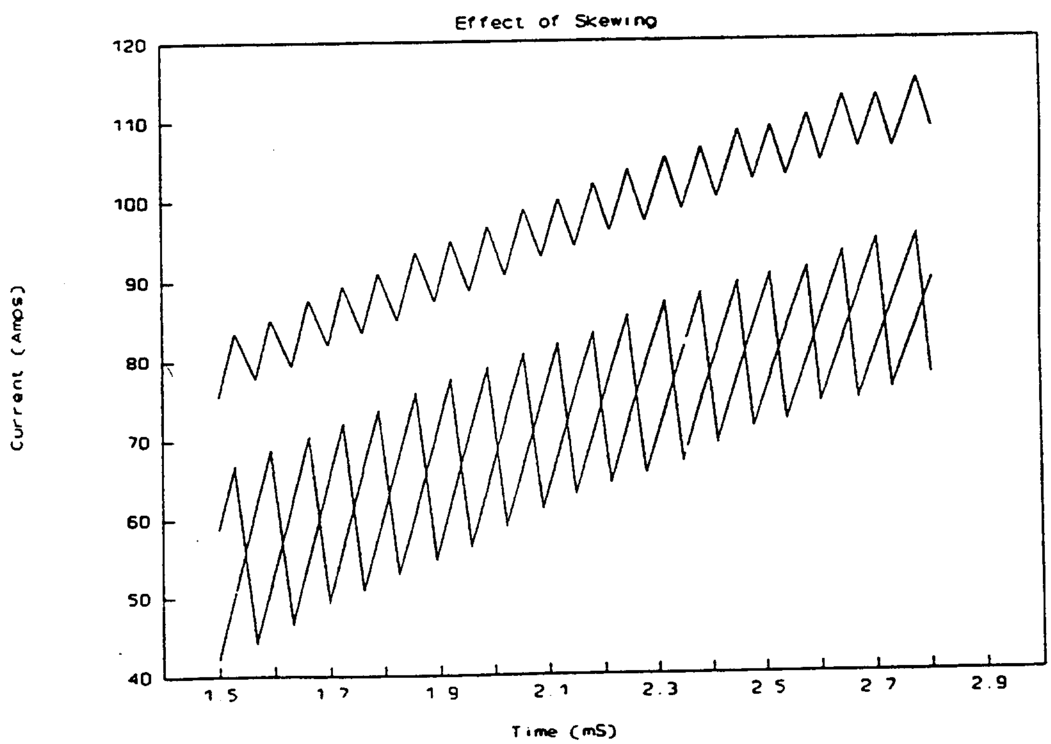


Figure 2 shows what we want to accomplish with skewing. The bottom two curves are two output waveforms that have been skewed 180 degrees apart using the computer model we developed. The top curve is the sum of the two bridges and shows the reduction in ripple current possible when bridges are skewed. This allows the reader to visualize the reduction by comparing the magnitude of single bridge ripple currents with the magnitude of the summed current. If the bridges were operating without skewing, the top wave current ripple would have the same magnitude as the bottom two waveforms.

The reduction in ripple is not 100% because the ripple current is a sawtooth shape. If the ripple current was a perfect V shape, the ripple current would cancel completely. At the zero crossing of the current waveform, the current is more uniform and does a better job of canceling.

Several options exist to look at the impact of skewing. The easiest option is to develop a current waveform running at a constant frequency, phase shift it, and add it to the un-phase shifted version. This gives an ideal output in that each waveform is identical and perfect. Rather than do this, we built a model of the bridge control circuit. This model does not operate to give a constant frequency output, rather it uses the variables that the real circuit will use and processes the data just like the real circuit. As a side benefit, the model allows tuning of the real circuit prior to building it. By looking at variables in the model, the effect of feedback and feedforward on the circuit can be seen. When several bridges are modeled, each bridge has its own model and runs independently of the other bridges. This gives the best picture of actual operating conditions that we can come up with.

With the model in place, the first step was to reduce frequency and inductance. Reducing frequency has two benefits. The first benefit is to allow the use of more conventional cores in the inductor. Today we are typically using inductors with a .002" thick steel core. By reducing the frequency, we hope to use a thicker (and less expensive) core material. Additionally, reducing the frequency of operation results in higher PCS efficiency due to the reduction in switching losses.

By reducing the inductance, the cost of the inductor should be reduced proportionately. Inductor cost roughly follows the formula $COST=\frac{1}{2}LI^2$. The baseline case for all the figures that follow is 3000 Hz operation, 200μH of inductance, is skewing positions and a dt of 4.17μS. The dt is how often the model is updated. As dt gets larger, the model operates less accurately.

Figure 3 shows the impact of the number of skewed module locations on THD. Two curves are shown. These correspond to the maximum 17 volts per battery (816 VDC) and the minimum 10.5 volts per battery (504 VDC). A single bridge has a THD of 123% at 17 volts and 62% at 10.5 volts per battery. The number of skewing locations has the most effect between 2 and 6. Beyond 6 skewing locations, the reduction in

THD is not as great, however there is benefit as the number of locations goes up. If an ideal bridge was used, the reduction at high numbers of bridges would be higher.

FIGURE 3

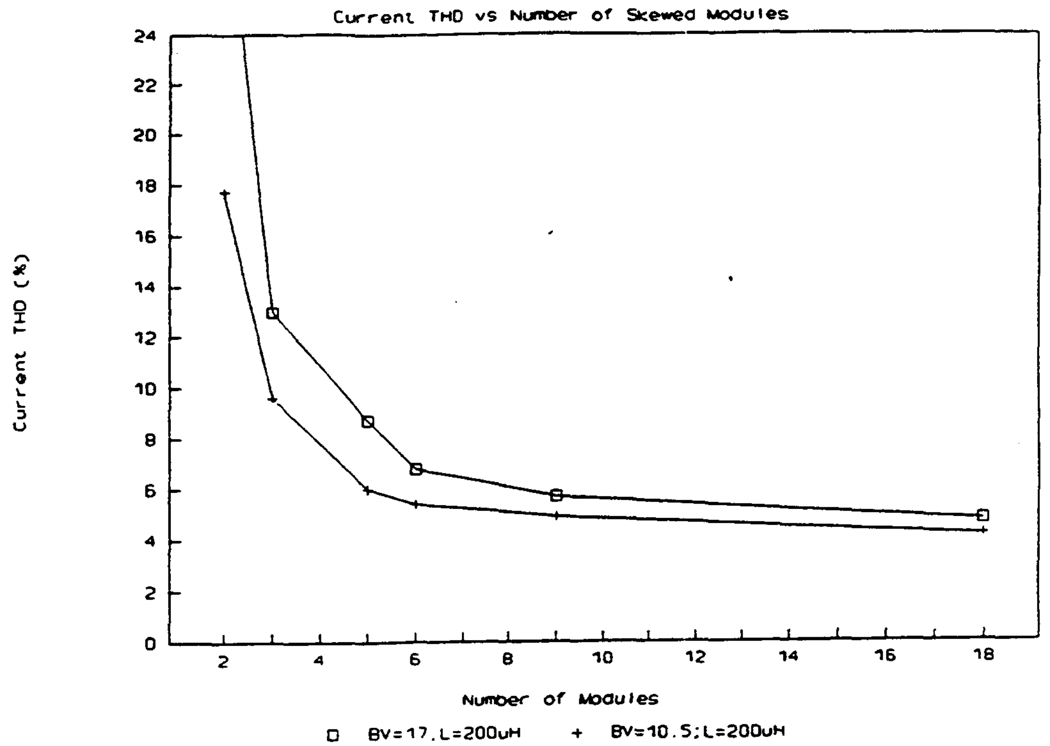


Figure 4 shows the effect of inductance on output current THD using 18 modules (skewing positions). As can be seen, as inductance increases the current distortion goes down. However, the distortion at 10.5 volts begins to go back up over 280μH. This is probably due to the errors introduced by operating at low DC voltages. Whatever the reason, there is a diminishing return in terms of output distortion as inductance is increased.

FIGURE 4

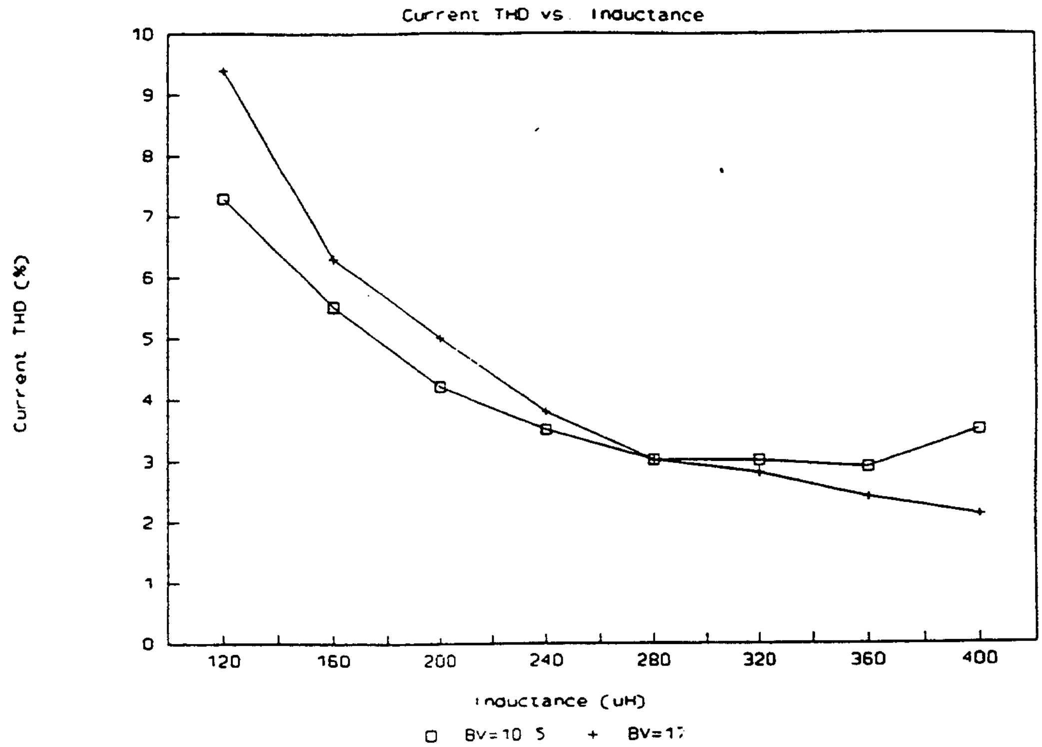


Figure 5 shows what happens to peak current as the inductance is varied. This has an impact on the size of the IGBT that is used. Omnion typically operates with peak currents between 100% and 130% of the current rating of the IGBT. If we go to low inductances to cut the cost of the inductor, we will pay more for the IGBT.

FIGURE 5

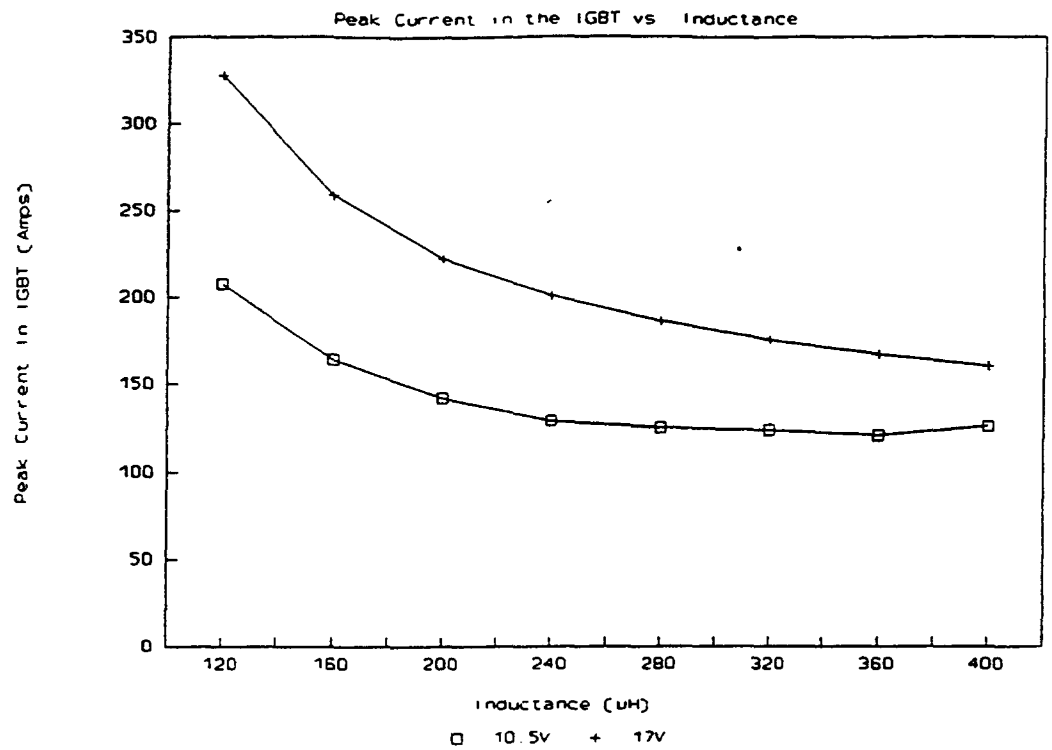


Figure 6 shows the sensitivity of THD to voltage at voltages between 10.7 and 17 volts per battery for 18 modules. By looking at the figure, the output THD goes up with battery voltage, but the sensitivity to battery voltage is not very great. This is in contrast to a single bridge, where the current THD doubles as the voltage goes over the same range.

FIGURE 6

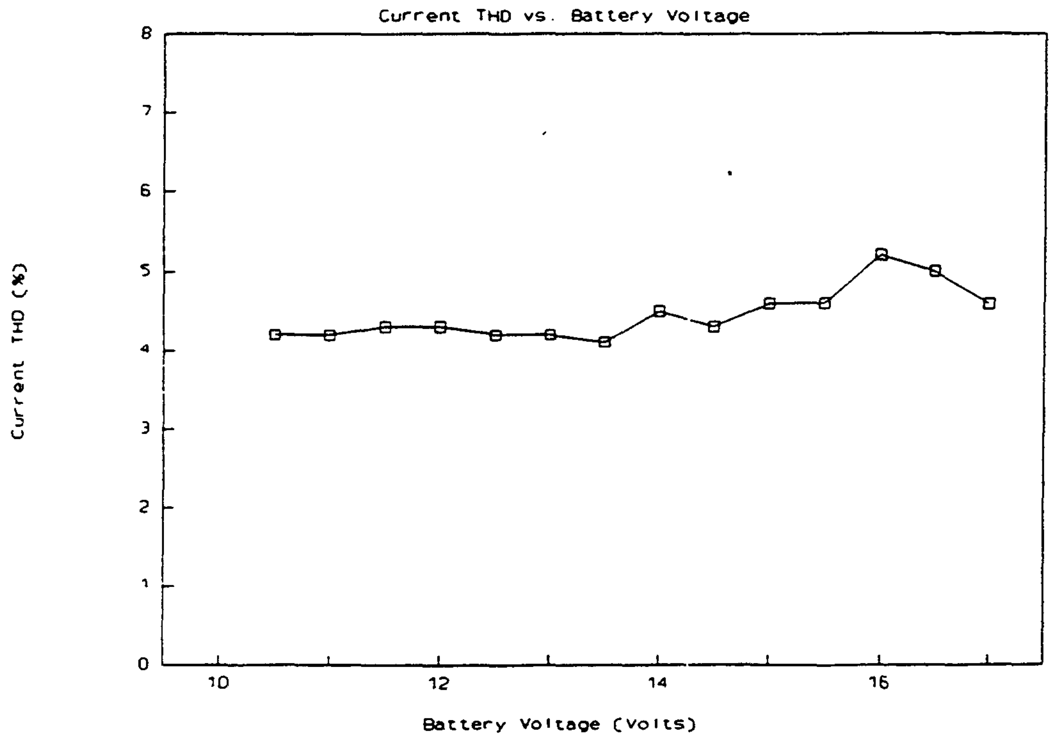


Figure 7 shows the effect of frequency on output THD using 18 modules and 200 μH inductors. This is a relatively minor impact. In addition to this impact, the peak current in the IGBT changes.

FIGURE 7

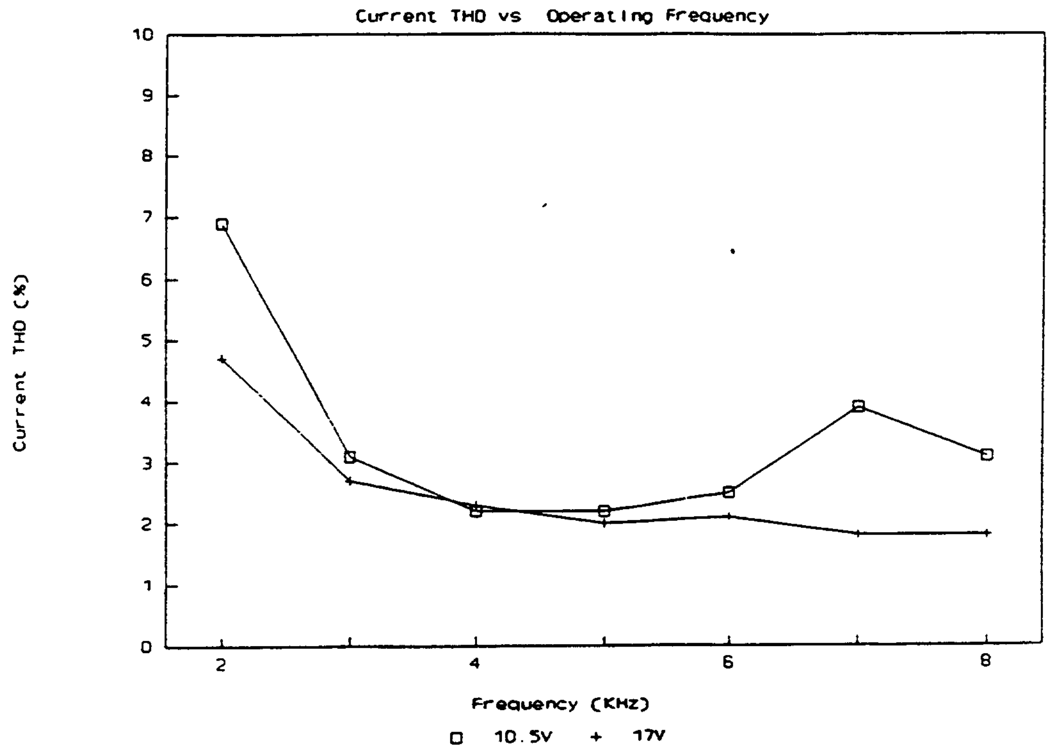
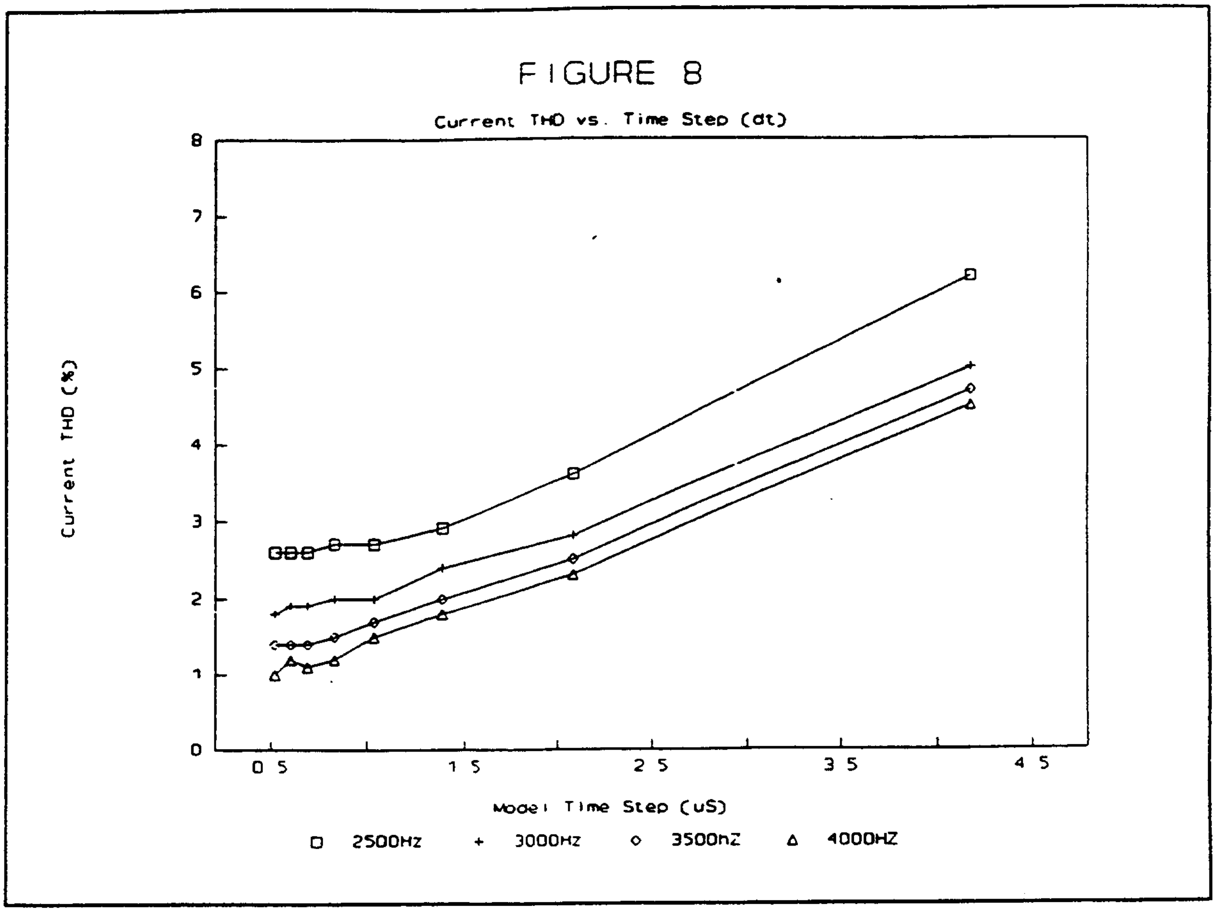


Figure 8 shows the effect of dt on current THD operating at different frequencies. We expect that the actual converter will use a dt of .5 to 1μS. In the actual converter, dt corresponds to a latch that is clocked on a regular basis. Other than this figure, all the graphs use a DT of 4.17μS. This gives a higher distortion, but the actual circuit will be subjected to noise that will induce some errors that resemble a longer dt.



Another variable that was considered was adding a delay to the circuit. A delay has a different effect than increasing dt. Delay puts a lag between the decision to switch an IGBT and the switching of the IGBT. This lag is due to delay in logic, optical isolation and storage time in the IGBT. It turns out that the effect of lag on the system is to add some 60 Hz error to the output. The impact of the error is to reduce the magnitude of the output waveform slightly. No impact is seen in current THD.

CONCLUSIONS

The result of this investigation is that both inductance and frequency of operation can be reduced while keeping the current THD below 5%. For the AC Battery PCS, the minimum configuration of the magnetics in terms of inductance and frequency is 200μH per phase of inductance and 3000 Hz operating frequency. This will require a 200 amp IGBT. If we increase the inductance to 400μH and the frequency to 4000 Hz we can get by with a 150 amp IGBT.

Below is a table that shows the current with different inductors at 60 Hz and at harmonics of the operating frequency. In the first line, the 3rd harmonic is shown as 7.2. This means that a bridge operating at 3000 Hz with 200μH of inductance has 7.2 amps of current at 9000 Hz. This data is used to design the inductor.

Operating	Induct			Harmonic Current (amps)							
Frequency	μH	60Hz	1st	2nd	3rd	4th	5th	6th	7th	8th	9th
3000	200	70.8	82.5	19.9	7.2	4.0	3.2	2.2	1.5	1.3	1.1
4000	200	68.7	62.7	14.7	5.3	3.0	2.4	1.9	1.4		
6000	200	69.8	41.5	10.0	3.5	2.3					
8000	200	70.7	31.0	7.8	3.1						
3000	200	68.2	83.9	19.9	7.6	4.2	3.4	2.3	1.7	1.6	1.4
3000	300	71.0	55.1	13.6	4.8	2.6	2.1	1.6	1.1	0.9	0.8
3000	400	68.6	41.7	10.2	3.9	2.3	1.9	1.4	1.1	1.0	1.0
3000	600	69.4	20.9	5.5	2.3	1.2	0.7	0.7	0.5	0.5	0.4
3000	800	71.5	15.3	4.2	1.7	0.8	0.5	0.4	0.3	0.3	0.3

Three options seem exist with regard to the inductor:

1) The first option is to build three separate inductors. This is what we have done in the past.

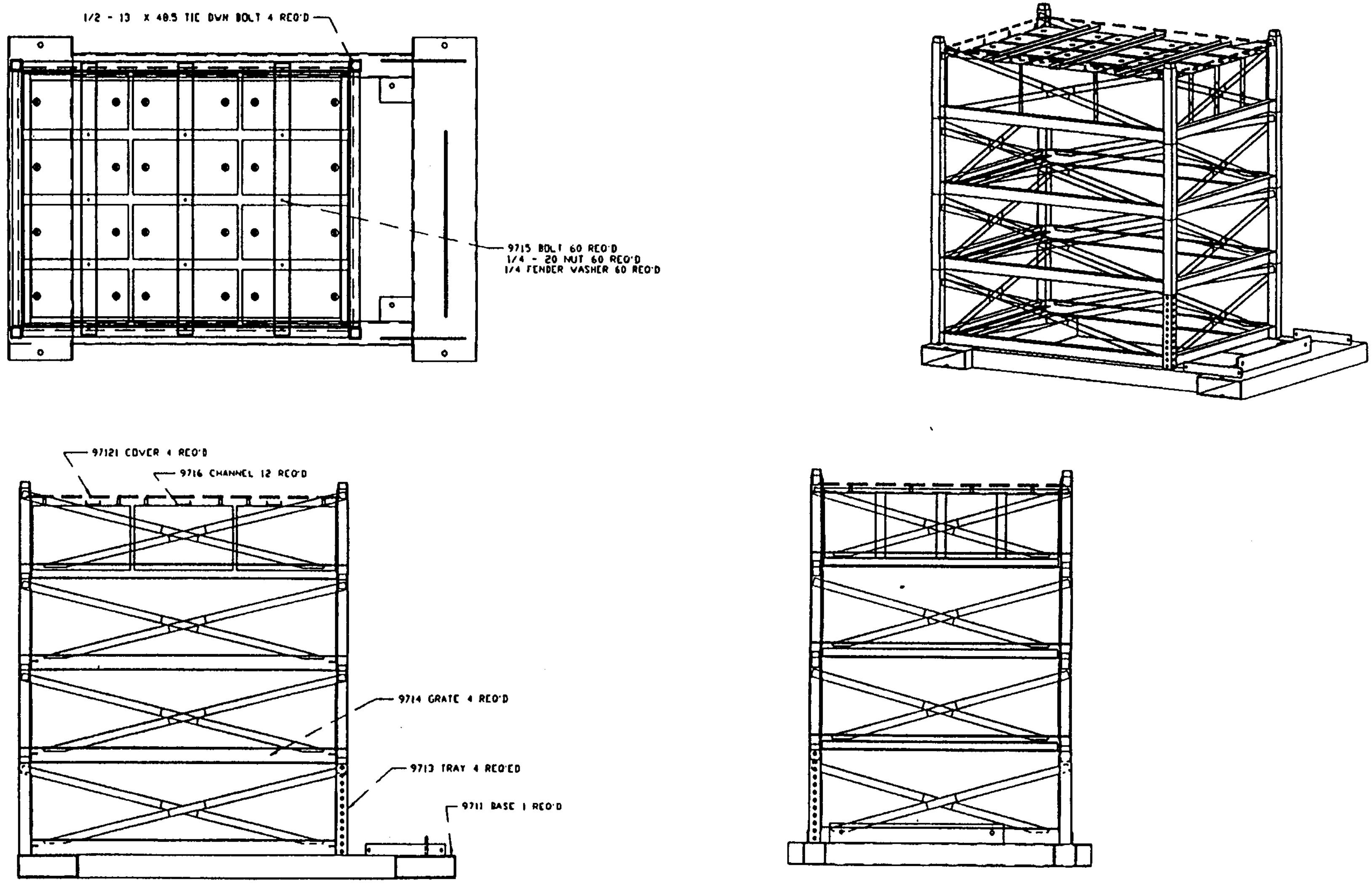
2) Second, the three inductors could be combined to make a three phase inductor. This reduces the parts count.

3) Finally, the inductors could become leakage inductance in a transformer.

The transformer would ideally be an isolation transformer with a 480 volt output. This option reduces the balance of system cost. Cost reductions are available in the elimination of a transformer for the container, and in lower currents inside the container. As configured, the converter output voltage is 255 line to line. The maximum current is 70 amps AC. This requires 100 amp rated equipment. By going to 480 volts, the maximum current is ≈37 amps AC. This is almost a 2:1 reduction and results in lower costs for disconnects, wire and circuit breakers.

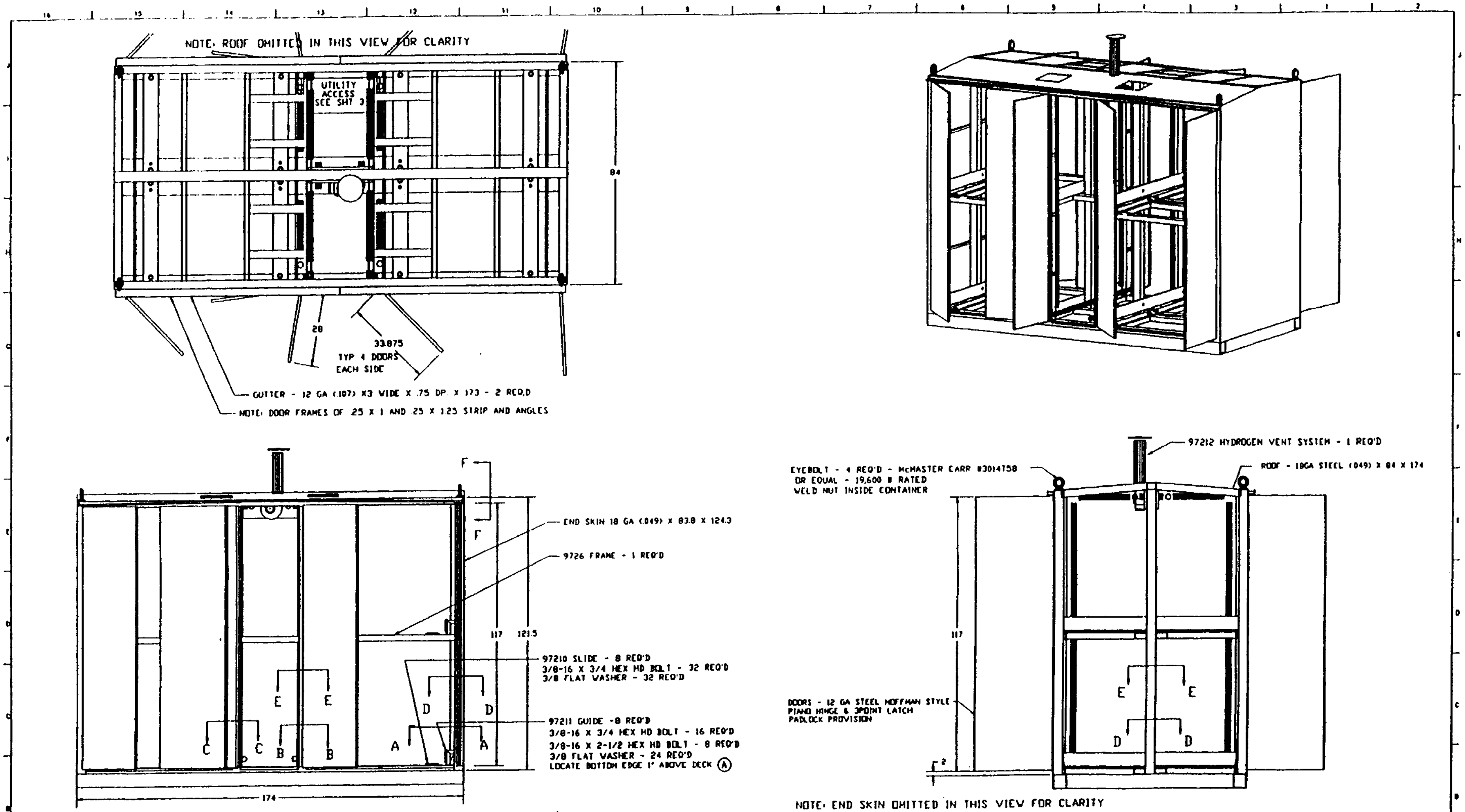
Mechanical Drawings

D



NOTES: 1. ASSY TO BE SHRINK WRAPPED FOR SHIPPING.
2. ALL EXPOSED WIRES TO BE INSULATED AND SECURED FOR SAFETY

OMNION POWER ENGINEERING		
SCALE N.T.S	DATE 01/26/93	
STATUS PRELIMINARY	CHECKED	APPROVED
TITLE MODULE ASSY-ACDC - DELCO		
SHEET 1 OF 1	DWG NO. MODASSYB	

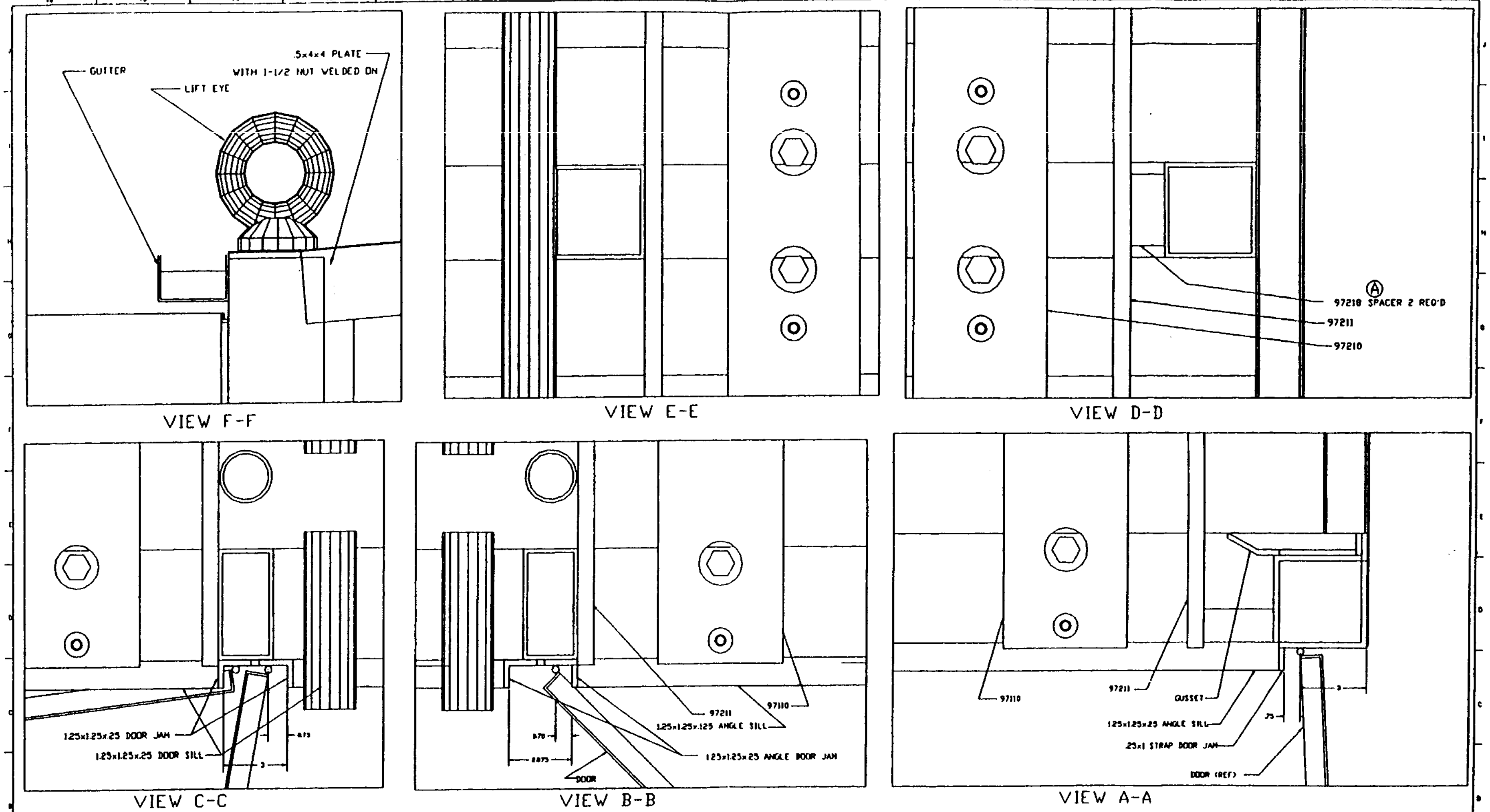


NOTES:
1. ALL WELDED CONSTRUCTION EXCEPT LIFT EYES
2. FINISH - ENAMEL PAINT (COLOR TO BE DETERMINED) INSIDE AND OUTSIDE. PER OMNION SPEC 900205
3. LOWER 6 INCHES OF INTERIOR TO BE SEALED WITH DUPONT NUCREL FLAME SPRAYED
4. INTERIOR TO BE INSULATED WITH 1 INCH MIN URETHANE FOAM - R 3.6 MIN
5. DOORS TO BE SEALED WITH FOAM WEATHERSTRIP TYPE SEALS

REV	DATE	DESCRIPTION	DRAWN	CHECKED	APPROVED
A	[illegible]	[illegible]	VEH		

OMNION POWER ENGINEERING

SCALE: VARIES	DATE: 03/24/93	DRAWN: VEH
STATUS: FINAL	CHECKED:	APPROVED:
TITLE: CONTAINER - AC BATTERY		
SHEET: 1 OF 3	DWG. NO. 9727	REV: A



REV	DATE	DESCRIPTION	DRAWN	CHECKED	APPROVED
A	[illegible]	ADDED 97218 SPACER CALLOUT - WAS SPACER	VEH		

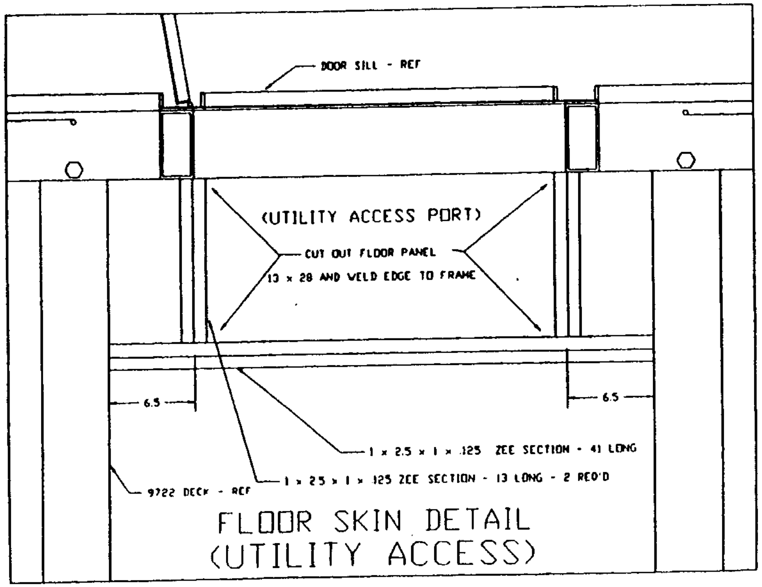
OMNION POWER ENGINEERING

SCALE: VARIES | DATE: 04/07/93 | DRAWN: VEH

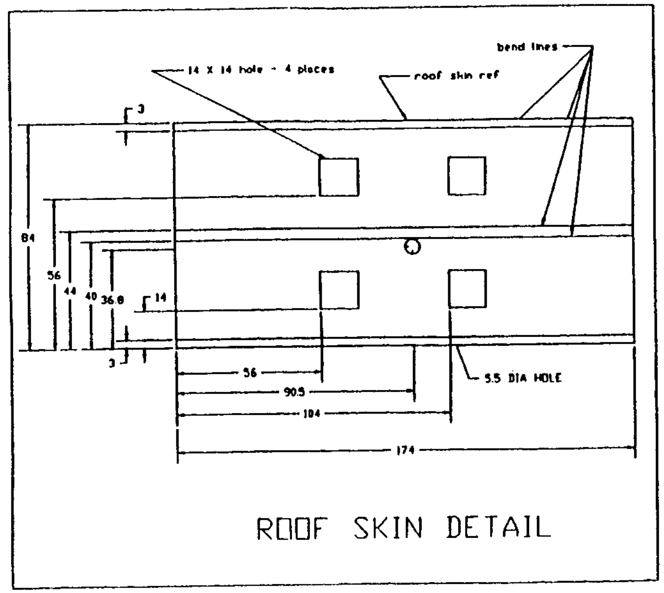
STATUS: FINAL

TITLE: CONTAINER - AC BATTERY

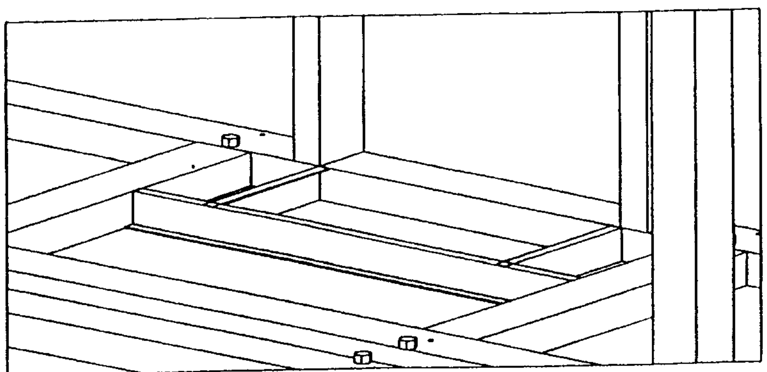
SHEET: 2 OF 3 | DWG. NO. 9727 | REV A



FLOOR SKIN DETAIL
(UTILITY ACCESS)



ROOF SKIN DETAIL



UTILITY ACCESS AREA (A)

REV	DATE	DESCRIPTION	DRAWN	CHECKED	APPROVED
A	[illegible]	ADDED UTILITY ACCESS VIEW	[illegible]		

OMNION POWER ENGINEERING

SCALE: VARIES	DATE: 04/08/93	DRAWN: WEH
STATUS: FINAL	CHECKED:	APPROVED:
TITLE: CONTAINER - AC BATTERY		
SHEET: 3 OF 3	DWG. NO.: 9727	REV: A

Structural Safety Study

E

AC BATTERY:
CONTAINER:
STRUCTURAL CALCULATIONS: Re: PG&E RFP No. 93-778-01

Structure:

4. Container handling is to be by crane via lifting eyes located at the four upper corners. Lift cables should be not less than 15 feet in length. The gross weight is 40,000#. The loads are transferred to the base via corner posts of 4x4x.25 steel angles. The lower half of the corner posts are boxed by welding additional 4x4x.25 angles toe to toe with the posts from the base to the upper deck. The base is 10x8x.25 w.t. rectangular tubing with four cross members in a classical ladder configuration. Eigh additional uprights connect the base to the top of the container. These are 4x4x.25 w.t. square tube and 2.5x5x.188 w.t. rectangular tube. The corner posts are stressed to 5200 psi in tension during lifting at one 'G' (factor of safety of 6.9).

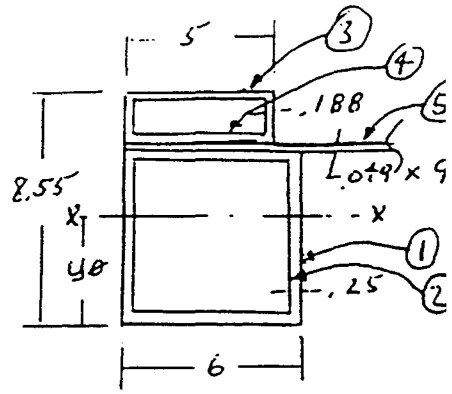
The ends, roof and one side are skinned with 14 ga. (.074) steel sheet fully welded along the edges and skip welded throughout the mid panel areas.

5. The ground footprint area of 41.9 square feet provides bearing surface pressure of 953 psf. The plan form of the base is shown on drawing 9721X.

AC BATTERY:
CONTAINER:
STRUCTURAL CALCULATIONS: SECTION PROPERTIES:

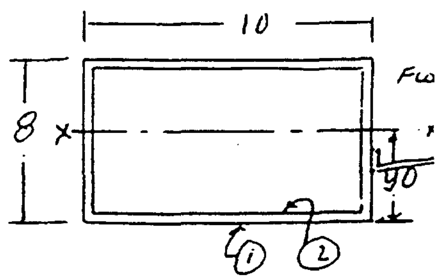
ORIGINAL BASE/DECK:

Element # 1 - b= 6 d= 6 y= 3
A= 36 I= 108 Y0= 3 Z= 36
Element # 2 - b= 5.5 d=-5.5 y= 3
A= 5.75 I= 31.744 Y0= 3 Z= 10.581
Element # 3 - b= 5 d= 2.5 y= 7.3
A= 18.25 I= 111.075 Y0= 5.945 Z= 18.683
Element # 4 - b= 4.625 d=-2.125 y= 7.3
A= 8.421875 I= 68.286 Y0= 4.364 Z= 15.647
Element # 5 - b= 9 d= .049 y= 6.025
A= 8.862875 I= 69.442 Y0= 4.446 Z= 15.616



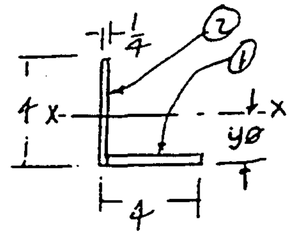
REVISED BASE:

Element # 1 - b= 10 d= 8 y= 4
A= 80 I= 426.666 Y0= 4 Z= 106.666
Element # 2 - b= 9.5 d=-7.5 y= 4
A= 8.75 I= 92.682 Y0= 4 Z= 23.17



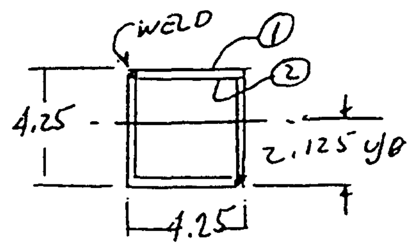
CORNER POST:

Element # 1 - b= 3.75 d= .25 y= .125
A= .9375 I= .004 Y0= .125 Z= .039
Element # 2 - b= .25 d= 4 y= 2
A= 1.9375 I= 3.039 Y0= 1.092 Z= 2.781



LOWER CORNER POST:

Element # 1 - b= 4.25 d= 4.25 y= 2.125
A= 18.0625 I= 27.187 Y0= 2.125 Z= 12.794
Element # 2 - b= 3.75 d=-3.75 y= 2.125
A= 4 I= 10.708 Y0= 2.125 Z= 5.039



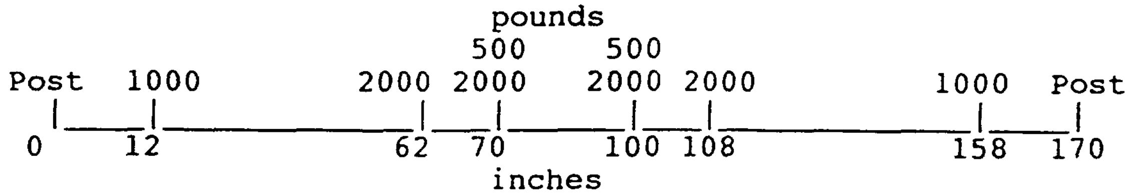
BASE STRESS/DEFLECTION ESTIMATE:

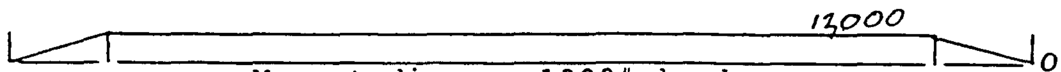
The base is loaded by the bottom modules at the bolt-down locations and by the structure from above by the vertical posts. The base is considered to be a simple supported beam along the door openings and uniformly supported by the skin along the back and ends.

Assuming the 10000# load at each corner is carried by the skin alone then the skin tension stress is S=10000/(.074*(42+87))=1047 psi. If this load is carried by the corner post alone the tension stress is S=10000/1.9375=5161 psi.

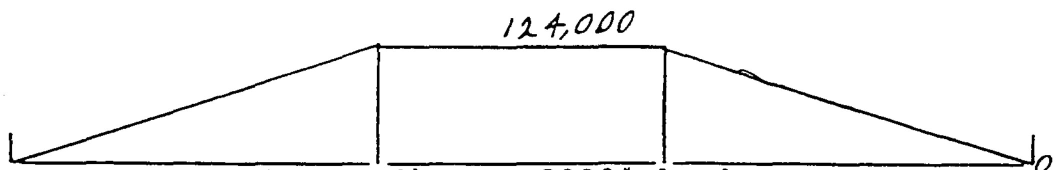
The loads transferred to the base member along the doorway side will be 1/4 of the lower module weight near the corner post, and 1/2 the lower module weight near the center, plus approximately 1/8 of the container structural weight and 1/2 of the upper module weight via the center posts.

The load pattern then becomes:

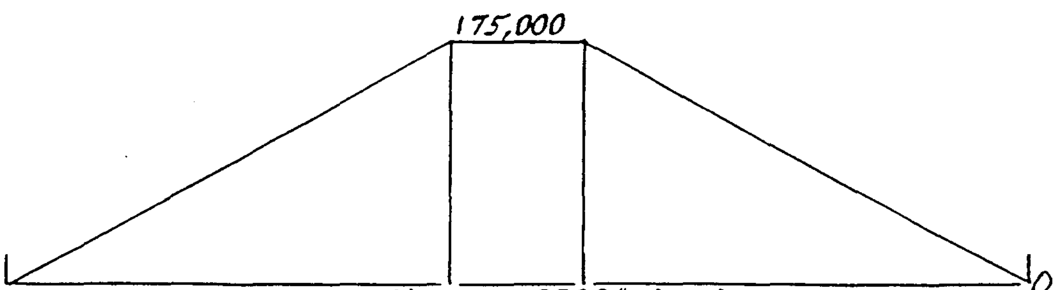




Moment diagram 1000# load



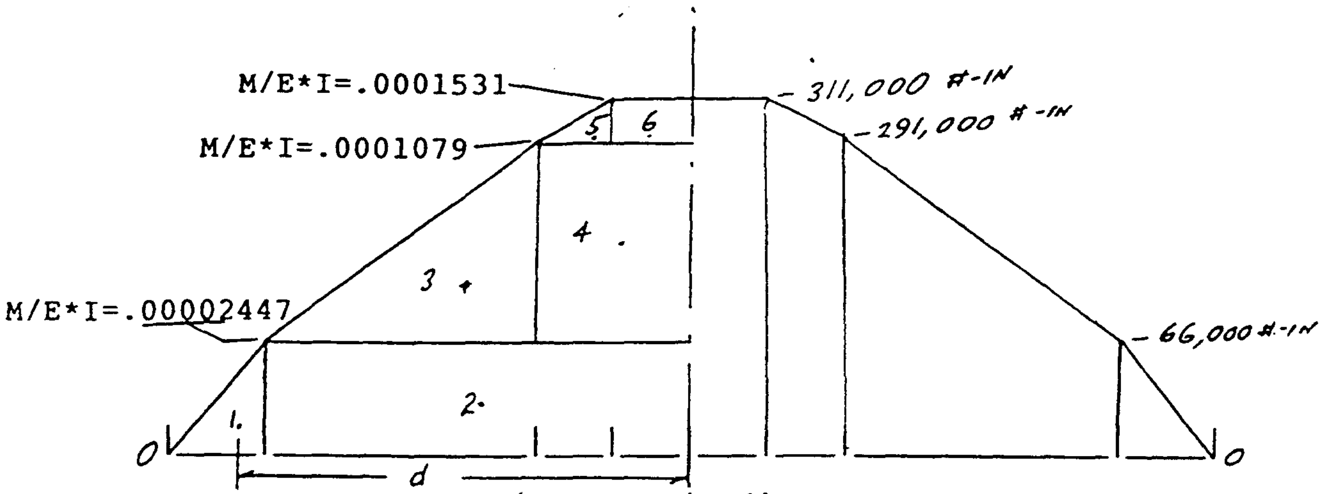
Moment diagram 2000# load



Moment diagram 2500# load

The maximum moment is then the sum of moments due to each contributing load and occurs in the center span of 30 inches at 311,000 in-lb. The max bending stress S=311,000/23.17=13,423 psi.

The deflection and end slope are determined by the Method of Elastic Weights (Mohr's Method): ref. E.F. Bruhn "Analysis and Design of Airplane Structures".



"M/EI" Moment diagram

DEFLECTION CALCULATION:

ELEMENT	BASE	d M/(E*I)	AREA	ARM (d-1/2)	AREA MOM
1	12	.00002447	0.0001468	77	-0.001175
2	73	.00002447	0.0017863	36.5	-0.086636
3	50	.00008343	0.0020858	39.7	-0.094484
4	23	.00008343	0.0019189	11.5	-0.141038
5	8	.000007416	0.0000297	17.7	-0.001996
6	15	.000007416	0.0001112	7.5	-0.008621
DEFLECTION AT CENTER = TOTAL AREA MOMENT =					-0.333951
END SLOPE AT POST (RADIANS)=TOTAL AREA=					0.0060787

This estimate analysis neglects the mitigating effects of the cross member torsional stiffness and the vertical member stiffness in reducing the deflection of the base beam.

Bending stress in the corner post at the base connection assuming full transfer of base slope to the post:

M=(slope)*E*I*4/L
M=.0060787*29,000,000*10.7*4/58=130,069 in-lb.

S=M/Z=130,069/5.039=25,800 psi.

Due to joint design the transfer will be approx. 50% and the stress will be 12,900 psi. for a Factor of Safety of 2.8+.

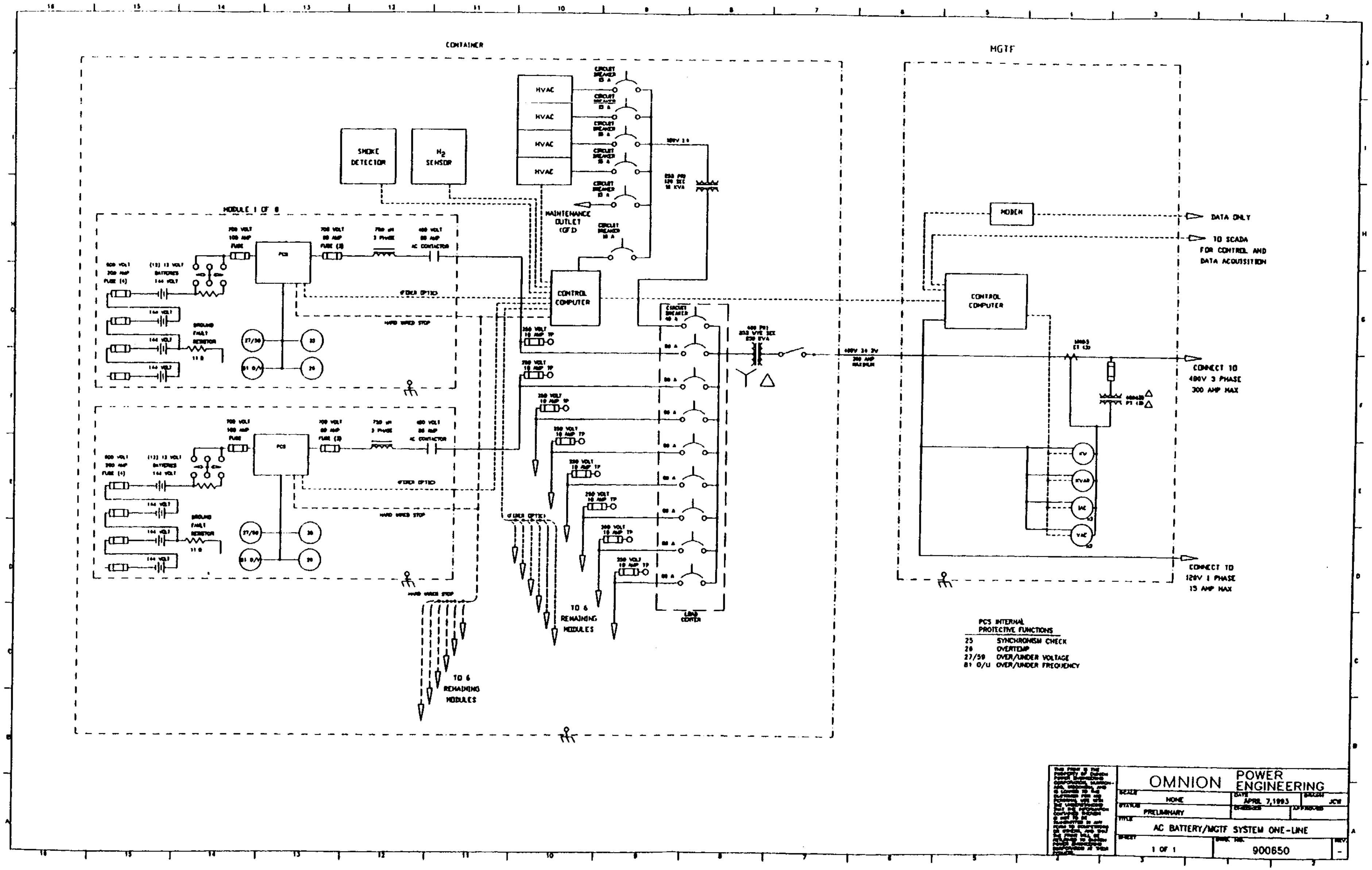
Submitted by:

W.E. Hunnicutt

W.E. Hunnicutt, PE
11/1/93

One-Line Electrical Diagram

F


CONTAINER
MGTF
HVAC
SMOKE DETECTOR
H2 SENSOR
CIRCUIT BREAKER
MAINTENANCE OUTLET (GFI)
CONTROL COMPUTER
MODULE 1 OF 8
PCS
FIBER OPTIC
HARD WIRED STOP
GROUND FAULT RESISTOR
AC CONTACTOR
LOAD CENTER
TO 6 REMAINING MODULES
MODEM
DATA ONLY
TO SCADA FOR CONTROL AND DATA ACQUISITION
CONNECT TO 480V 3 PHASE 300 AMP MAX
CONNECT TO 120V 1 PHASE 15 AMP MAX
PCS INTERNAL PROTECTIVE FUNCTIONS
25 SYNCHRONISM CHECK
26 OVERTEMP
27/59 OVER/UNDER VOLTAGE
81 O/U OVER/UNDER FREQUENCY
OMNION POWER ENGINEERING
NONE
APRIL 7,1993
JCW
PRELIMINARY
AC BATTERY/MGTF SYSTEM ONE-LINE
1 OF 1
900650

Summary of PG&E AC Battery Test Plan

G

PG&E
AC Battery Test Plan

Presented by:

Greg Ball
Electrotek Concepts, Inc.
March 25, 1993

AC Battery Test Outline

- Protection/Pre-Parallel Inspection
- Start-Up and Internal Protection
- Steady State Performance
  - Initial Block Discharge Cycle
  - Harmonics & Power Factor Control Characterization
  - Block Cycle Characterization
  - Load-Follow Cycle Characterization
  - Auxiliary Load Characterization
- Dynamic Response
  - Speed and Stability
  - Interconnect Protection Tolerances
  - Islanding
- Long Term Behavior

Protection/Pre-Parallel Inspection

- **Objective**

  Complete all utility-side measures required for interconnecting the AC Battery to the Modular Generation Test Facility (MGTF) circuit.

- **Tasks**
  - PG&E EE representative to verify proper phase connections, battery system breaker operation and relay settings, etc.
  - Define breaker configuration procedures for all anticipated operating modes of the battery system on the two-bus MGTF network. Define any limitations for the battery's parallel operation with other MGTF components.
  - Familiarize all test personnel with updated MGTF Operating Safety Procedures.

Start-Up and Internal Protection

- Objective

  Complete field start-up procedure as defined by Omnion and perform control-circuit level verification of the module and container level safety functions.

- Tests
  - Step by step start-up of module control power, PCS units and finally container system as a whole; synchronize to grid.
  - Use a signal generator to "fool" control system into thinking there are abnormal operating conditions, verify the appropriate system response (shutdown).
  - Other safety tests using actual problem conditions.

Internal Protection Tests

- Smoke
- Hydrogen
- Over-Temperature
- Ground Fault
- U/O AC Voltage
- U/O Frequency
- Overcurrent (AC)
- DC Injection
- Vdc Tolerances

- Emergency Stop
- Synchronization
- Blown Fuse Detect
- Power Supply Check
- Check-Sum Error
- Serial Time-Out

Steady State-Initial Block Discharge

- **Objective**

  Complete a full power discharge-charge cycle to characterize rated operation of the battery.

- **Tests**
  - 1 hour constant rate (block) discharge.
  - Heavy monitoring using SCADA/DAS, BMI harmonic and spectrum analyzer, oscilloscope, EPRI module DAS, and audio noise /RFI devices.
  - Special attention to early trouble signs, e.g discrepancies in string voltages, temperatures, cell voltages (EPRI modules), premature end-of-discharge, etc.
  - Programmed CI-CV-CI charge, again heavily scrutinized.

Steady State - Harmonics/Power Factor

- Objective

  Characterize the power conditioning system (PCS) harmonic distortion, noise and power factor control over their full power ranges in discharge mode.

- Tests
  - Discharge mode: In a single discharge cycle, ramp down from full power in ~50 kW increments.
  - Record PCS efficiency noise, harmonics.
  - At each increment, characterize (incrementally) available consuming and producing VAR output.
  - Watch for consistency of kW output, any changes as DC voltage decreases, etc.

Steady State - Block Load Tests

- Objective
  Characterize the constant power discharge performance and ratings for 2 to 8 hour discharge durations.
- Tests
  - A series of full cycle tests conducted once or twice for each of the block load rates (2 to 8 hours).
  - Special attention to battery capacity variation for given rate, round-trip efficiencies, dc-dc efficiencies, HVAC usage, parameter variations over course of cycles (i.e. as function of DC voltage), module capacities compared to historic cell data (string vs. individual).

Steady State - Load Follow Tests

- Objective

  Characterize the load follow (sine curve) discharge performance and ratings for 2 to 8 hour discharge durations.

- Tests
  - A series of full cycle tests conducted once or twice for each of the load follow rates (2 to 8 hours).
  - Special attention to determining peak kilowatt level attainable for a given discharge duration.
  - Attention will also be paid to battery capacity variation for given rates, round-trip efficiencies, dc-dc efficiencies, HVAC usage, parameter variations over course of cycles.

Steady State - Auxiliary Load Tests

- **Objective**
  To characterize the auxiliary load and tare losses of the battery system.
- **Tests**
  - Monitor system power usage in shutdown and standby modes.
  - Record HVAC power usage over its load variations (if any).
  - Power profile (BMI) measurements on separate control power circuit - circuit includes HVAC, control computer, and maintenance outlet.
  - Additional load measurements on PCS power circuit in standby mode.

Dynamic Response - Speed & Stability

- Objective

  Characterize the battery system's speed and stability in response to commanded changes in mode of operation.

- Tests
  - Utilize a high-rate storage oscilloscope to monitor single-phase waveforms as they respond to mode changes:
    - » Standby <> Full Discharge
    - » Low Discharge <> Full Discharge
    - » Full Discharge <> CC Charge (auto)
    - » Full Discharge <> Full (maximum) Charge
    - » Low Power, No VARs <> Low Power, Full VARs
    - » Standby <> Full VARs

Dynamic Response - Protection

- Objective

  To the extent possible, characterize system's ability to detect and respond to actual bus (480 V) voltage (and frequency) variations.

- Tests
  - Bus manipulation via impedance loop, bus loading, or larger scale signal generator.
  - Characterize trip voltages, frequencies and delays as applicable.

Dynamic Response - Islanding

- **Objective**

  Characterize the ability of the battery system (PCS) to detect a loss-of-utility condition and prevent extended run-on and islanding.

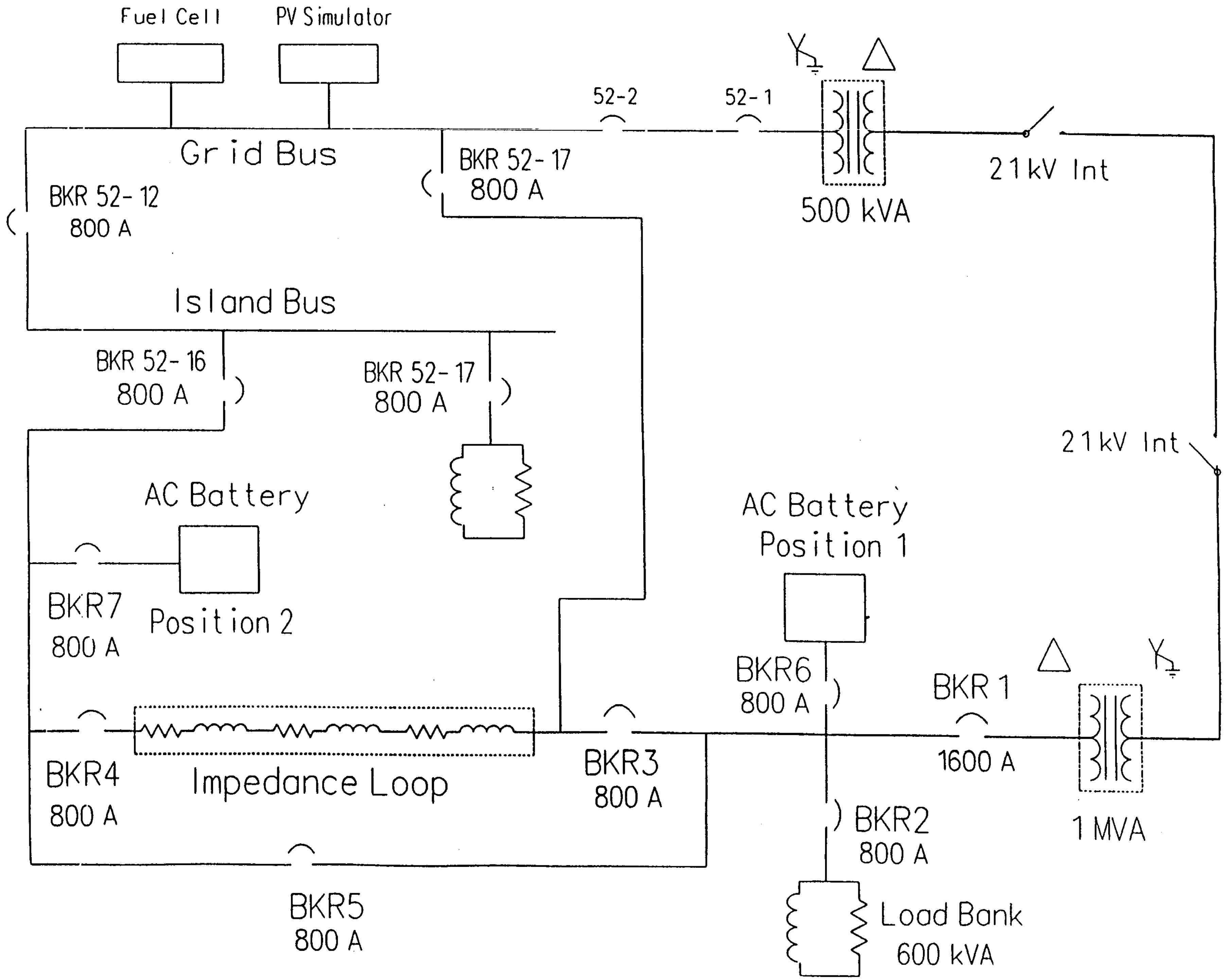
- **Tests**
  - Using a parallel load bank, measure time to shutdown for a large range of real power-to-load ratios upon opening utility breaker ("Kitamura Curve").
  - Additional sequence of tests at balanced real power loads.
  - Sequence of balanced and near-balanced reactive power load tests - including rotating machine load (load bank cooling fan).

Long-Term Behavior Tests

- Objective

  Characterize the battery system cycle life, long term degradations of capacity and efficiency, and battery, module & container life failure modes.

- Tests
  - Set-up a relatively unattended, repetitive test sequence to cycle the battery using predetermined load follow discharge - charge cycles. Load follow curves will include programmed profiles from PG&E transformer charts.
  - Automated database fed by DAS/SCADA system and EPRI module DAS.
  - Program database to plot trends, degradation, battery and module loss, etc.



Fuel Cell
PV Simulator
Grid Bus
52-2
52-1
500 kVA
21kV Int
BKR 52-17
800 A
BKR 52-12
800 A
Island Bus
BKR 52-16
800 A
BKR 52-17
800 A
AC Battery
Position 2
BKR7
800 A
AC Battery
Position 1
BKR6
800 A
BKR 1
1600 A
1 MVA
21kV Int
BKR4
800 A
Impedance Loop
BKR3
800 A
BKR2
800 A
BKR5
800 A
Load Bank
600 kVA

Unresolved Issues

- Unattended Operation
- Impedance Loop - VAR Compensation Tests
- Opportunity Charging
- Internal Protection Test Logistics
- Bus Manipulation Tests
- Accuracy of Efficiency Measurements
- Maximum Slew Rates
- SCADA/DAS Configuration
- System Location on 480 V Circuit

Production Cost Estimate

H

Production Cost Estimate for the 250-kW Modular, Factory-Assembled Battery Energy Storage System

General

Costs presented and detailed here constitute Omnion Power Engineering's best estimate of expected production costs based on development work and construction of the AC Battery 250-kW prototype designed and constructed under Sandia National Laboratories (SNL) contract number 78-8198. Estimates are based on production quantities as indicated. An important assumption made in preparing the information below is that all units would be shipped and installed at separate sites. Figures shown are production costs and do not include manufacturer's markup. The numbers will change as economies of scale are realized for installations with several units. Correspondingly, start-up service and annual maintenance will also be reduced.

Report Format

The format of this report is the same as that used in contract documents provided by SNL and complies with its standard cost reporting requirements. The format was intended to provide a standardized life-cycle cost basis to compare the 250-kW AC Battery system with other competing battery energy storage system (BESS) technologies and designs.

The need for a common basis on which to compare differing technologies and system topologies is evident when examining the unique features that the 250-kW AC Battery system possesses compared to traditional BESSs. The 250-kW AC Battery system buses together numerous battery strings through specialized high-voltage DC switchgear and custom-built converters, aggregating AC power from multiple AC Battery modules. This modular, building-block approach provides greater flexibility in meeting system sizing and layout requirements.

The AC Battery concept permits complete factory assembly and testing of system containers prior to transport to the customer site. The AC Battery system utilizes commercially available, high-volume production components of proven reliability. These components are factory assembled and tested under rigorous quality control standards to create a fully operational, highly reliable, modular BESS.

Table H-1 explains the individual component cost categories considered for comparing the alternative technologies on a 20-yr product life-cycle basis. Outside of the individual product performance variables of the compared technologies, the table provides a common, equalized basis to aid in making financial decisions. Added to the original SNL format provided is the life-cycle replacement cost of batteries. Table H-2 is a manufacturing, installation, and service cost summary for the AC Battery system. Table H-3 shows component cost as a percentage of total production cost.

Table H-1. Cost Component Categories

Cost Component	Cost Component Description
A. AC Source/Load Interface to Battery System	1. New lines to serve installation (e.g., 4, 12, 69 kV) 2. Transformer between utility voltage and battery system AC voltage (e.g., 69 kV; 480 V) 3. Protection devices (e.g., switches, breakers, fuses)
B. Power Conversion System	1. AC switchgear/disconnect 2. Rectifier/inverter 3. DC switchgear/disconnect 4. Protection devices (e.g., switches, breakers, fuses)
C. Batteries and Accessories	1. Electrical a. Batteries (cells, tanks, membranes) b. Interconnects c. Protection devices (e.g., switches, breakers, fuses) d. Chargers 2. Mechanical a. Racking/physical support b. Watering/heating/air and fluid pumping systems c. Safety equipment (e.g., ventilation, fire equipment, detectors, respirators, spill troughs)
D. Monitors & Controls	1. Monitors/diagnostics a. Power conversion system (PCS) b. Batteries (strings and cells) 2. Controls a. PCS b. Batteries c. Protection devices
E. Facilities	1. Foundation and structure (and associated labor) 2. Materials 3. Lighting/plumbing 4. Finish grade/landscape 5. Access road 6. Grounding/cabling 7. Heating, venting, and cooling (HVAC)
F. Financing	
G. Transportation	
H. Taxes(1)	
I. Services	1. Project management 2. Installation 3. Studies (e.g., relays, harmonic filters) 4. Data gathering/trending 5. Permits
J. Operation and Maintenance (36-mo. host site periods)	1. Service contract 2. Cell/fluid recycling/replacement 3. Training 4. Inspections
K. Replace Batteries	
(1) Not included here and amount depends on the location (state) and customer tax status.	

Table H-2. AC Battery Manufacturing, Installation, and Service Cost Summary (based on 1994 data)

Cost Component (see Table H-1)	Single Unit Cost (in $000)	25-49 Units/yr (in $000)	50+ Units/yr in ($000)
A & E.[1] AC Source/Load Interface to Battery System	$84.8	$84.8	$84.8
B, C, D, E,[2] & G. Turn-key System[3]	378.2	321.5	302.6
F. Financing	N/A	N/A	N/A
H. Taxes [4]	N/A	N/A	N/A
I. Services [5]	N/A	N/A	N/A
J. Operation and Annual Maintenance	25.2	25.2	25.2
K. Replace Batteries [6]	38.4	38.4	38.4
Total Production Cost	$526.6	$469.9	$451.0

(1) Includes all "facilities" costs except for the transportable AC Battery system container. Does not include a distribution transformer, which would be required only if the output voltage is other than 480 VAC.
(2) Includes the structure, HVAC, safety, and other "facilities" costs that are integral to the AC Battery system container.
(3) The AC Battery system integrates battery submodels into its modular design with all required interconnects, protection devices, chargers, physical support, environmental control, and safety systems. Thus cost component C (Batteries and Accessories) is included in the turnkey cost.
(4) Not included here and amount depends on the location (state) and customer tax status.
(5) Start-up service is included in Turnkey Systems cost.
(6) The batteries used have a 2-yr life expectancy. Thus, their replacement is every 2 years over a 20-year life.

Table H-3. AC Battery Component Cost as a Percentage of Total Production Cost

Cost Component	Single Unit Cost (in $000)	25-49 Units/yr (in $000)	50+ Units/yr in ($000)
A & E. AC Source/Load Interface to Battery System	16.1%	18.0%	18.8%
B, C, D, E, & G. Turnkey System	71.8%	68.4%	67.1%
F. Financing	N/A	N/A	N/A
H. Taxes	N/A	N/A	N/A
I. Services	N/A	N/A	N/A
J. Operation and Annual Maintenance	4.8%	5.4%	5.6%
K. Replace Batteries	7.3%	8.2%	8.5%
Total Production Cost	100.0%	100.0%	100.0%

Intentionally Left Blank

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